U.S. Department of Energy
FreedomCAR and Vehicle Technologies, EE-2G
1000 Independence Avenue, S.W.
Washington, D.C. 20585-0121

FY 2006

DOE FreedomCAR and Vehicle Technologies Program Advanced Power Electronics and Electrical Machines Annual Review Report

Pollard Technology Conference Center
Oak Ridge, Tennessee
August 15-17, 2006

Prepared by:

Oak Ridge National Laboratory

Mitch Olszewski, Program Manager

Submitted to:

Energy Efficiency and Renewable Energy
FreedomCAR and Vehicle Technologies
Vehicle Systems Team

Susan A. Rogers, Technology Development Manager

October 11, 2006

Table of Contents

Introduction

This report is a summary of the Review Panel at the FY06 DOE FreedomCAR and Vehicle Technologies (FCVT) Annual Review of Advanced Power Electronics and Electric Machine (APEEM) research activities held on August 15-17, 2006, at the Pollard Technology Conference Center in Oak Ridge, Tennessee (see Appendix A for agenda). The projects evaluated in this document supports the Department of Energy (DOE), and the evaluations in conjunction with this annual review are major inputs utilized by the DOE in making its funding decisions in future fiscal years. One hundred eleven participants attended the review in person, via webcast, and/or via phone (see Appendix B for attendee listing).

The objectives of the meeting were to:

- Review and evaluate DOE FCVT APEEM FY06 research accomplishments and FY07 plans for research and industry/university collaborations.
- Provide an opportunity for program participants to help shape the DOE sponsored R&D program so that the highest priority technical barriers and challenges are addressed
- Foster interactions among the universities, industry, and national laboratories conducting the R&D.

Review Presentations

During the opening session on the first morning, the DOE Advanced Power Electronics Technology Manager, Susan Rogers, provided an overview of the FCVT APEEM Program and activities that were not reviewed including SBIR awards, future solicitations, and crosscut activities with the DOE Vehicle Systems Program. Following Ms. Rogers' presentation, an overview of the FCVT APEEM R&D strategy was presented by Mitch Olszewski of Oak Ridge National Laboratory (ORNL). During the three-day review, session leaders presented project overviews for FY06 and previews for FY07 projects and principal investigators presented project-related plans and progress. Project presentations on the characterization of capacitor materials and carbon foam thermal management materials were also given by principal investigators in the Advance Materials Technologies area, but were not reviewed by the review panel members.

Project-Level Presentation Selection

The DOE program manager, working with staff and session leaders from ORNL, NREL and NSWCCD, examined the entire program portfolio and selected the slate of projects to be reviewed. All projects in the portfolio were considered for review, regardless of their stage of maturity, with the primary focus on the key projects. The following projects were reviewed.

- *Capacitor Development*
  - Embedded Capacitors for Power Electronic Systems
  - Glass Dielectric Capacitors
  - Polymer Film and Nano-Dielectric Capacitors

- *Electric Machine*s
  - Advanced Traction Motor Development
  - Development of Improved Powder for Bonded Permanent Magnets
  - Flux Weakening and CPSR Enhancement Techniques
    - Extending the CPSR of Synchronous Reluctance Traction Drive Motor
    - Control of Fractional Slot Motors Made with Concentrated Windings

- Interior Permanent Magnet Reluctance Machines (6K and 16K with BFE
- Uncluttered CVT Machine

- *Systems*
  - Benchmarking of Competitive Technologies/Component Characterization
  - Fully Integrated HEV Traction Motor Development Using TE and Film Capacitor Innovations

- *Power Electronics*
  - Advanced Converter Systems for High Temperature (Air cooling) HEV Environments
  - Cascade Multilevel Inverter for Fuel Cell Based HEV
  - DC to DC Converter for Fuel Cell and Hybrid Vehicles
  - High Temperature (105°) Inverter Development
  - Integrated DC/DC Converter for Multi-Voltage Bus Systems
  - Wide Bandgap Materials

- *Thermal Control*
  - Advanced Thermal Interface Materials to Reduce Thermal Resistance
  - Air Cooling for Power Electronics
  - Dynamic and Steady State Modeling to Identify, Over Various Drive Cycles, Component and System Performance Efficiency and Thermal Loads
  - Identifying the Barriers and Approaches to Achieving High Temperature Coolants
  - Low Thermal Resistance IGBT Structure
  - Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling
  - Thermal Control for Inverters and Motors

Reviewer Panel Selection

In order to acquire a broad and balanced spectrum of expertise and perspectives across the review panel, multiple sources were queried for nominations. The DOE program manager and staff established qualifying criteria that individual candidates were required to meet for selection to the review panel. The qualifying criteria included an in-depth knowledge of the subject area and no real or perceived conflicts of interest. It was important that the in-depth knowledge was "demonstrated" in terms of publications, patents, professional awards or positions, or other recognized credentials in the subject area. Candidates were required to perform a self-assessment and identify possible conflicts-of-interest raise. A matrix was drawn up to indicate the various expertise levels needed for the areas being reviewed. Reviewers who met the qualifying standards for individual reviewers represented diversity in backgrounds and experience sufficient so the panel collectively covered the range of expertise required. In addition to satisfying the qualifying criteria, it was a review goal to choose reviewers who were motivated to speak out, who have knowledge and perspectives that the program may not have, and who would challenge the program to improve.

Table 1 – Review Panel Members	
Fiegenschuh, Karl	Ford Motor Company
Fulton, Dave	Remy, Inc.
Garg, Vijay	Ford Motor Company
Lai, Jason	Virginia Tech University
McCluskey, Pat	University of Maryland
Mazzola, Mike	SemiSouth Laboratories, Inc
Mehall, Mark	Ford Motor Company
Melfi, Mike	Rockwell Automation
Miller, John	Maxwell Technologies , Inc.
Shedd, Tim	University of Wisconsin
Smith, Greg	General Motors
Taylor, Ralph	Delphi Electronics and Safety

Analysis Method for Project Evaluation

As shown in Table 1, a total of 12 review panel members participated in the annual review. A total of 23 project presentations were given at the meeting for review (excluding overview presentations from DOE staff and lead laboratory R&D staff), and a total of 224 review evaluation forms were received from the review panel members (not every panel member reviewed every project). Review panel members were asked to provide numeric scores (on a scale of one to four, with four being the highest) for three aspects of the research on their review form (a sample is shown in Appendix C). The three aspects were:

- Relevance to overall DOE objectives and mission;
- Approach to perform the research and development;
- Technical accomplishments and progress toward achieving the project and DOE goals.

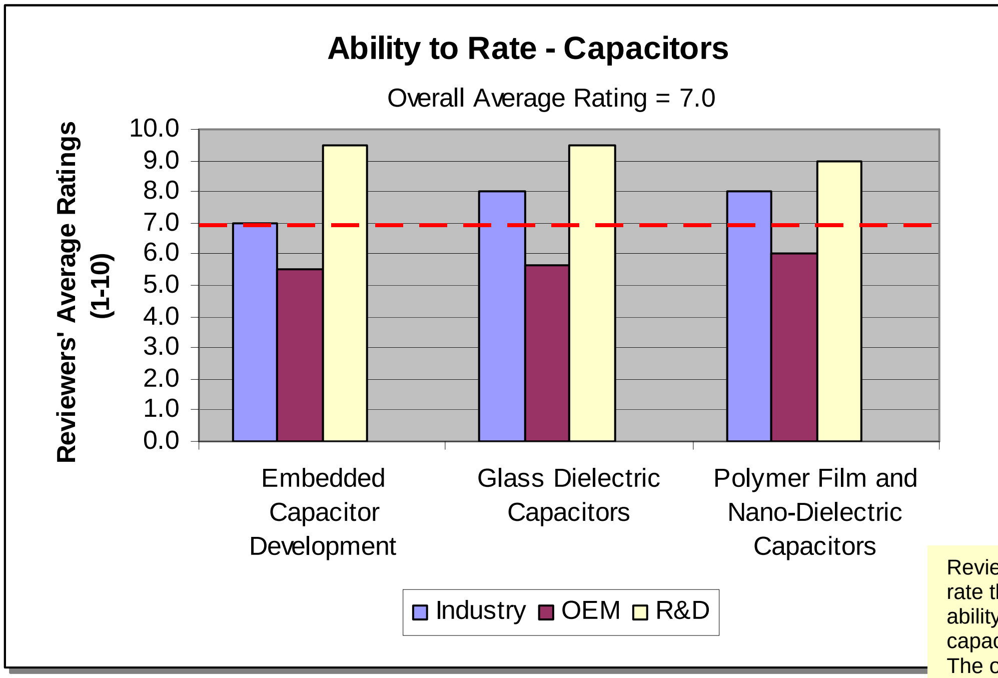
Reviewers were also asked to provide qualitative comments on the three research aspects, as well as on the specific strengths and weaknesses of the project and any recommendations for additions or deletions to the work scope. After the review, the principal investigators were given the opportunity to provide feedback on the reviewers' comments (reviewers remained anonymous). These comments, along with the quantitative scores, were placed into a database for easy retrieval and analysis. A summary of ratings is shown in Appendix D. Complete ratings and comments, along with principal investigators' responses are shown in Appendix E. Reviewers of a given project provided a numeric score for each of the three criteria, but did not necessarily provide qualitative comments.

In addition to numeric scores for the aspects above, reviewers also provided ratings on their ability to rate the specific presentations and the project's importance to the FreedomCAR APEEM Program (see Summary of Project Evaluation Feedback section below).

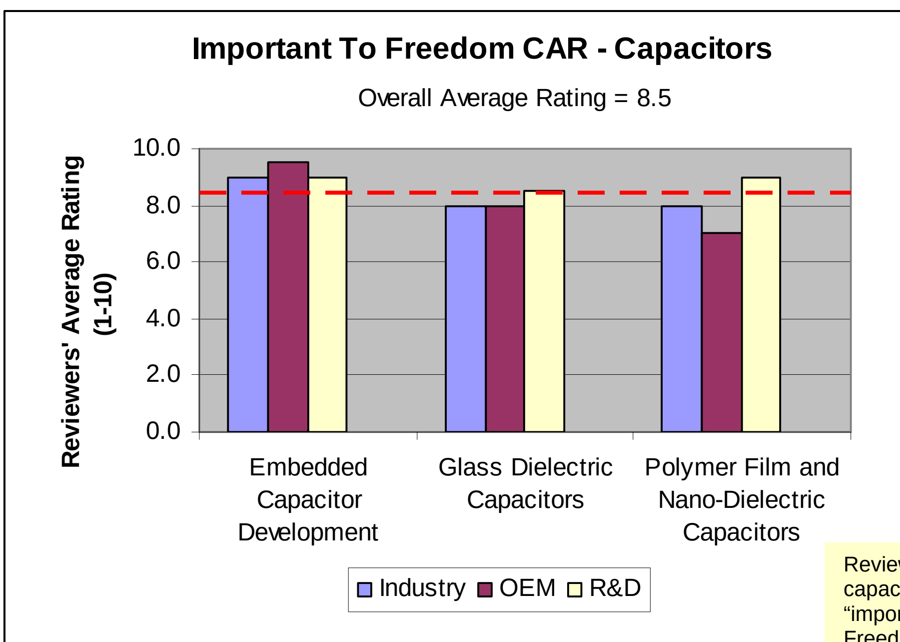
Summary of Project Evaluation Feedback

The following information provides summaries of the projects that were reviewed and their ratings.

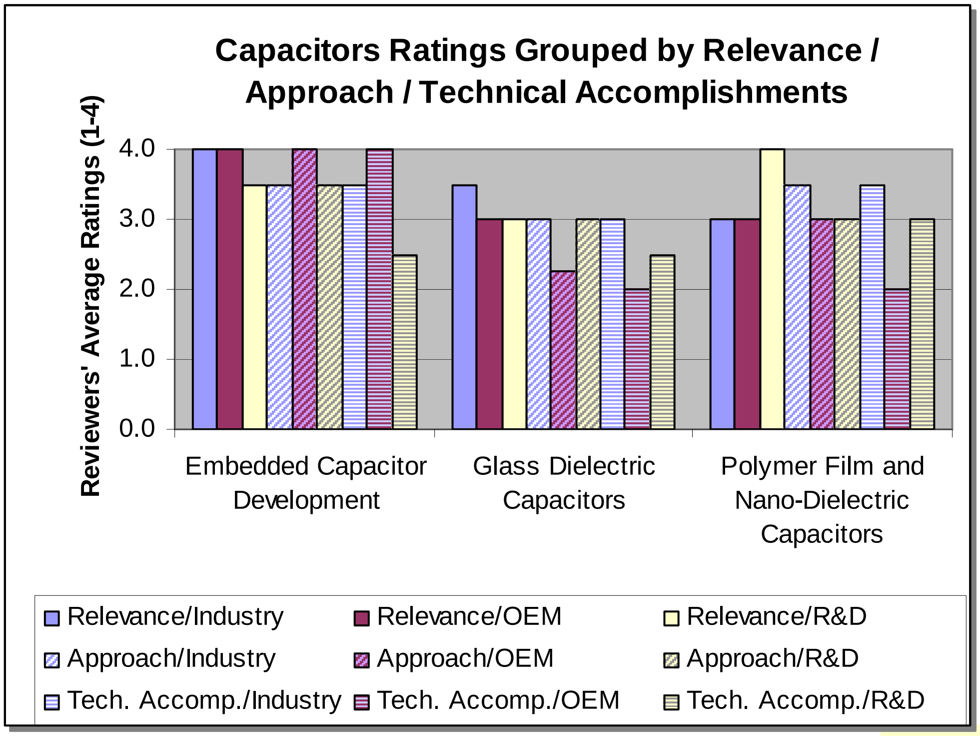
Summary of Project Evaluation Feedback for Capacitors



Reviewers were asked to rate themselves on their own ability to evaluate each capacitor project.
The overall average of all the responses from all reviewers was **7/10**.
Responses ranged from 1 (lowest) to 10 (highest).



Reviewers also rated each capacitor project on its “importance to meeting FreedomCAR goals.
The overall average response from all projects and reviewers was 8.5**/**10.
Responses ranged from 1 (lowest) to 10 (highest).



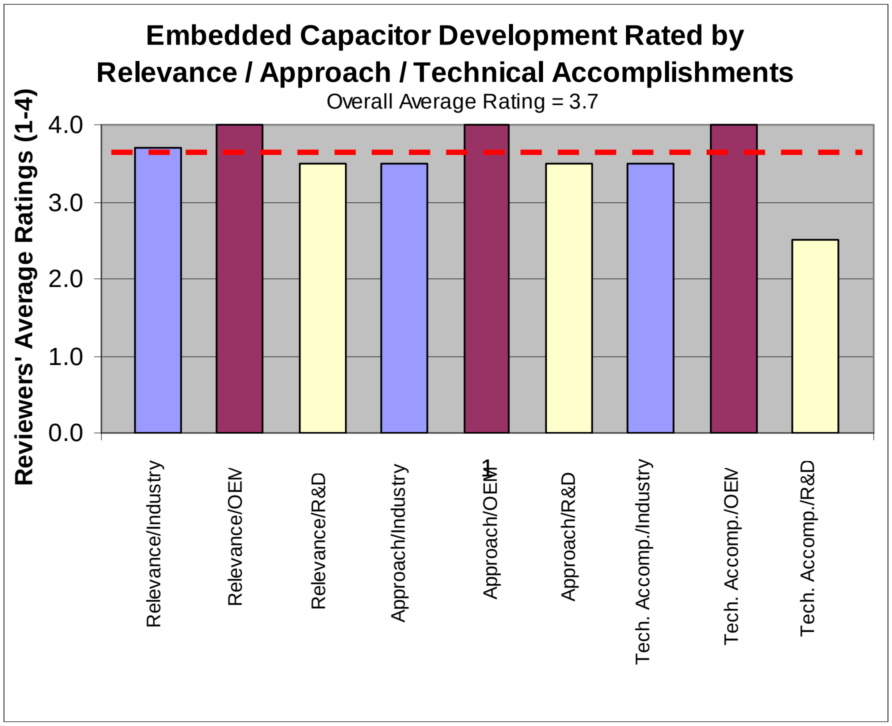
Reviewers rated each capacitor project on its "relevance," "approach," and "technical achievement." Responses ranged from 1 (lowest) to 4 (highest).

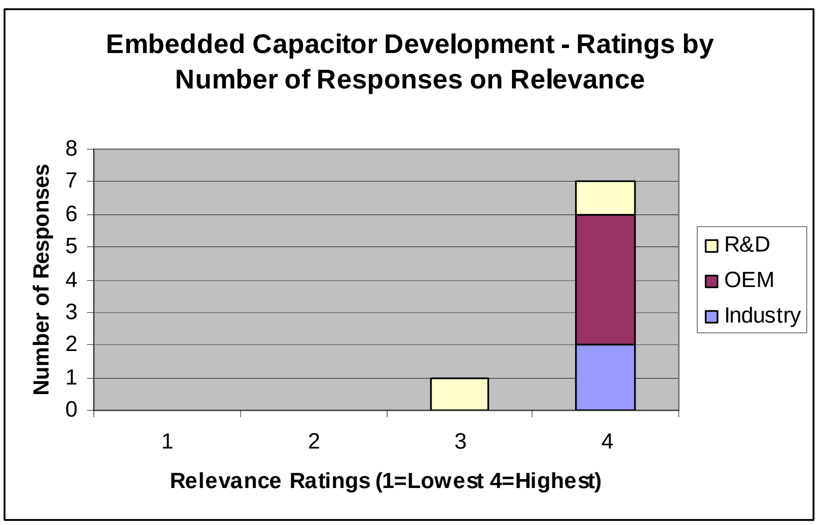
Summary of Project Evaluation Feedback for Specific Capacitor Projects

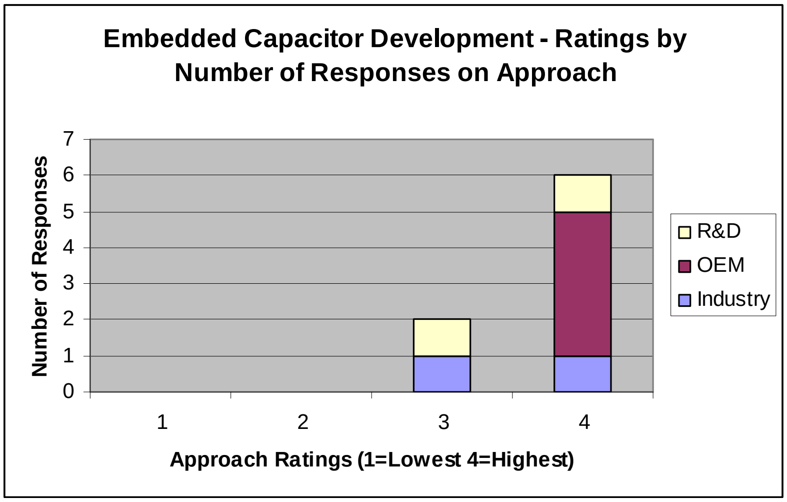
Embedded Capacitors for Power Electronic Systems
David Kaufman – Argonne National Laboratory (Argonne)

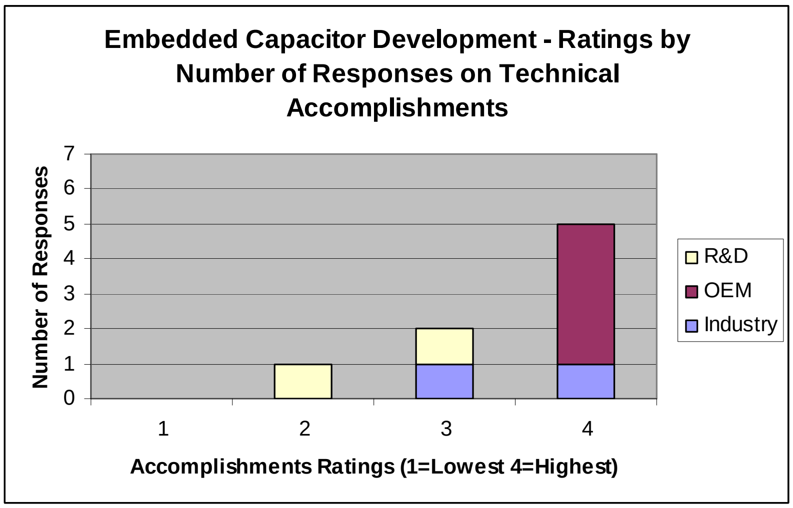
Project Summary: Argonne National Laboratory (Argonne)'s development effort is based on high permittivity ferroelectrics with high breakdown electric fields and insulation resistance in order to produce multilayer capacitors embedded directly into printed circuit board for automotive application. In FY06 Argonne continued the development of film-on-foil technology with the goal of deposition on bare copper foil. A process was identified for producing large area film-on-foil sheets the standard size of a printed wire circuit board. This processing routine can be transferred to a commercial production environment. In addition collaboration was developed with DSI and Delphi as industrial partners. In FY07 efforts will focus on scaling up the film-on-foil technology to 18" x 24" foils as well as completing the parameters for bare copper foil processing.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.


Embedded Capacitor Development Rated by
Relevance / Approach / Technical Accomplishments
Overall Average Rating = 3.7
Reviewers' Average Ratings (1-4)
4.0
3.0
2.0
1.0
0.0
Relevance/Industry
Relevance/OEM
Relevance/R&D
Approach/Industry
Approach/OEM
Approach/R&D
Tech. Accomp./Industry
Tech. Accomp./OEM
Tech. Accomp./R&D


Embedded Capacitor Development - Ratings by
Number of Responses on Relevance
Number of Responses
8
7
6
5
4
3
2
1
0
1
2
3
4
Relevance Ratings (1=Lowest 4=Highest)
R&D
OEM
Industry





Industry Comments:

- Approval of program plan with metrics for validation of performance against targets
- Valuable contribution to US FreedomCar provided risks are addressed
- Scalability of PLZT to power inverters in terms of size, voltage and temperature needs to be determined
- Component development needs attention
- Printed wire board flexing and vibration modes need to be examined
- Leveraging of other resources raises concern for projected progress

OEM Comments:

- Approach is logical and data based showing transition from laboratory materials to development of component hardware
- Accomplishments are very good
- Details on design need to be provided in order to make fair assessment
- Persistent efforts in addressing technical challenges acknowledged
- Assembly of bulk capacitors need to be addressed

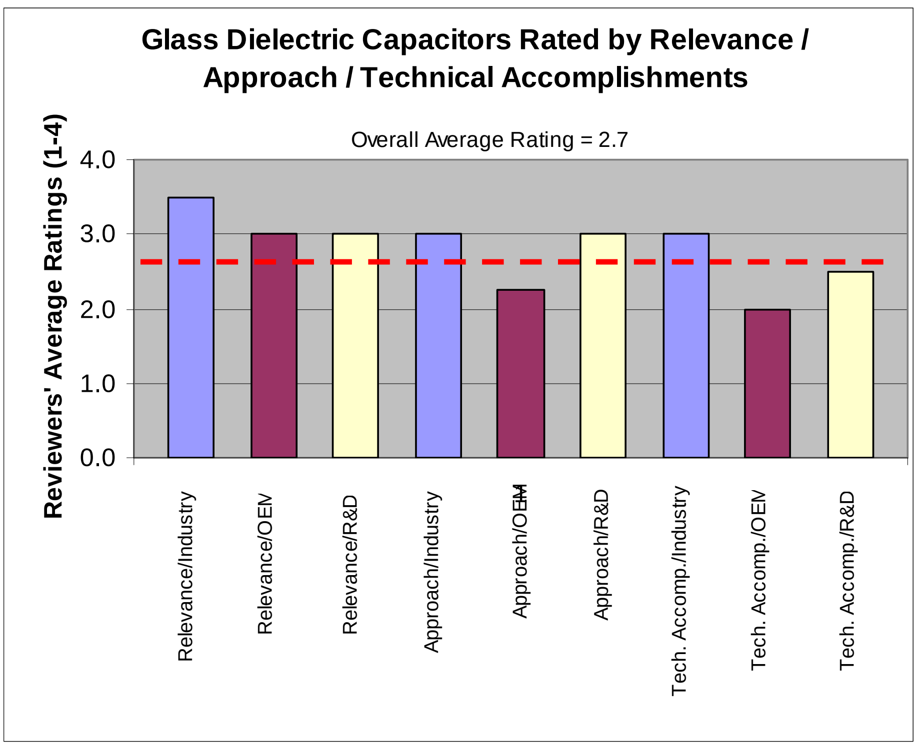
R&D Comments:

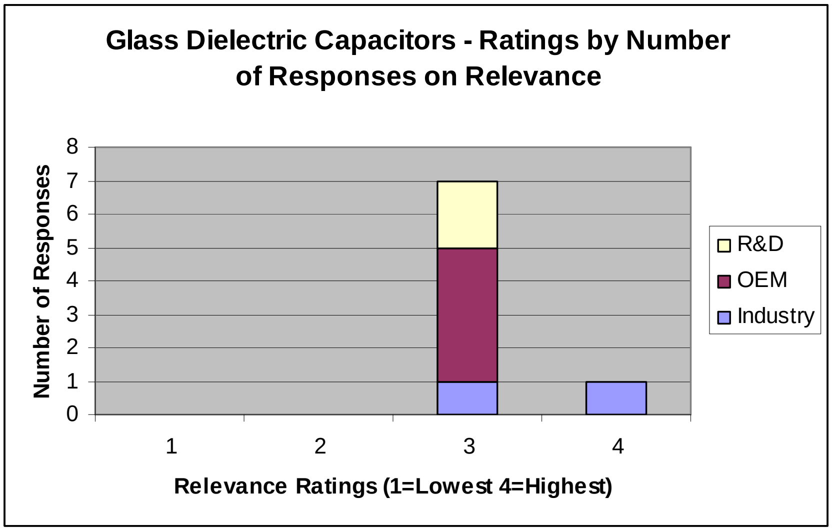
- Significant advantages in weight, cost, size and reliability with performance goals achievable through low cost manufacturing process
- Risk limited by utilization of established processes
- Data presentation lacking on nickel foil to assess progress

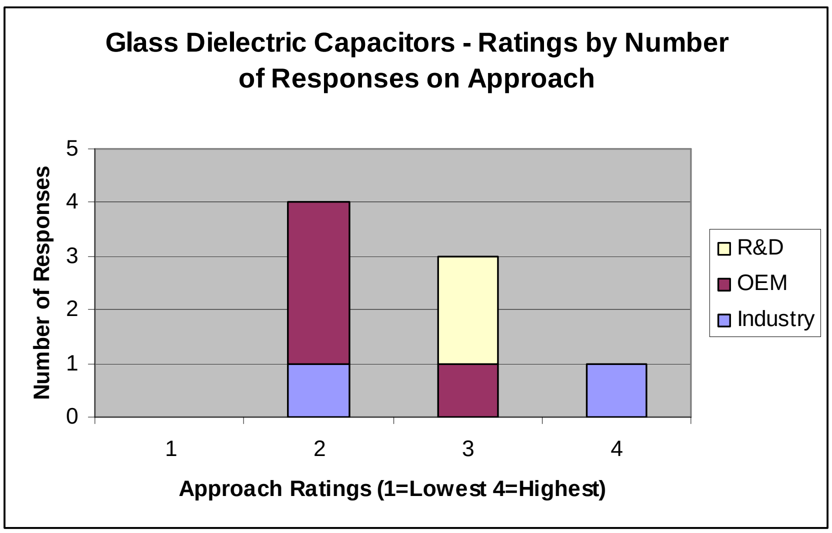
Glass Ceramic Capacitors for DC Bus Capacitors
Michael Lanagan – Penn State University (PSU)

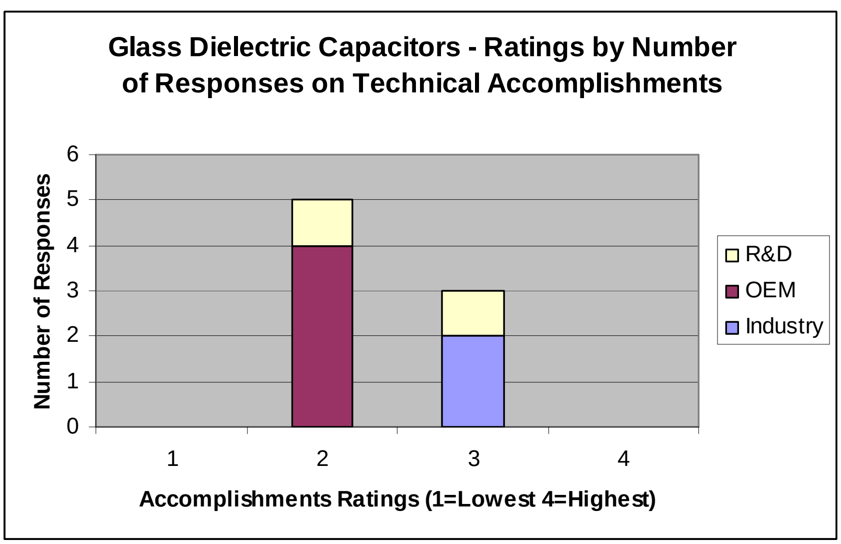
Project Summary: PSU is addressing the development of glass ceramic capacitors based on glass technology currently used in large-scale flat panel displays. . Large-scale processes have already been developed for flat-panel displays so raw materials are available for glass capacitor manufacturing. This new capacitor technology promises high ripple current capability at elevated temperatures. In FY06, dielectric properties of Schott and Corning Glass samples were tested and showed promise for high temperature capacitor applications. Initial reliability tests demonstrated that these commercial materials can operate at high temperature. FY07 efforts will focus on the development of graceful failure mechanisms, dielectric breakdown testing and additional reliability testing at high temperature.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.




Glass Dielectric Capacitors - Ratings by Number of Responses on Relevance
Number of Responses
0
1
2
3
4
5
6
7
8
1
2
3
4
Relevance Ratings (1=Lowest 4=Highest)
R&D
OEM
Industry


Glass Dielectric Capacitors - Ratings by Number of Responses on Approach
Number of Responses
0
1
2
3
4
5
1
2
3
4
Approach Ratings (1=Lowest 4=Highest)
R&D
OEM
Industry


Glass Dielectric Capacitors - Ratings by Number of Responses on Technical Accomplishments
Number of Responses
0
1
2
3
4
5
6
1
2
3
4
Accomplishments Ratings (1=Lowest 4=Highest)
R&D
OEM
Industry

Industry Comments:

- Clearly valuable S&T; benefit to automotive application questioned
- Combination of academia and commercial collaboration but concern raised in reaching a clear endpoint
- Milestones need to be defined better
- Glass ceramic technology promising but potential issues with mechanical integrity and tangent delta at high temperature
- Exploration of two glass suppliers' materials with down select in FY07 excellent
- Scale up of fabrication capability needs to be addressed
- Voiding or pitting of glass dielectric is a concern in terms of fracture
- Life cycle testing methodology in industry is not standardized

OEM Comments:

- Data lacking to fairly assess project
- Technical details and results need to be presented to support claims
- Concerns raised in terms of glass dielectrics and harsh under the hood operating environment
- Failure mechanism discussion needed

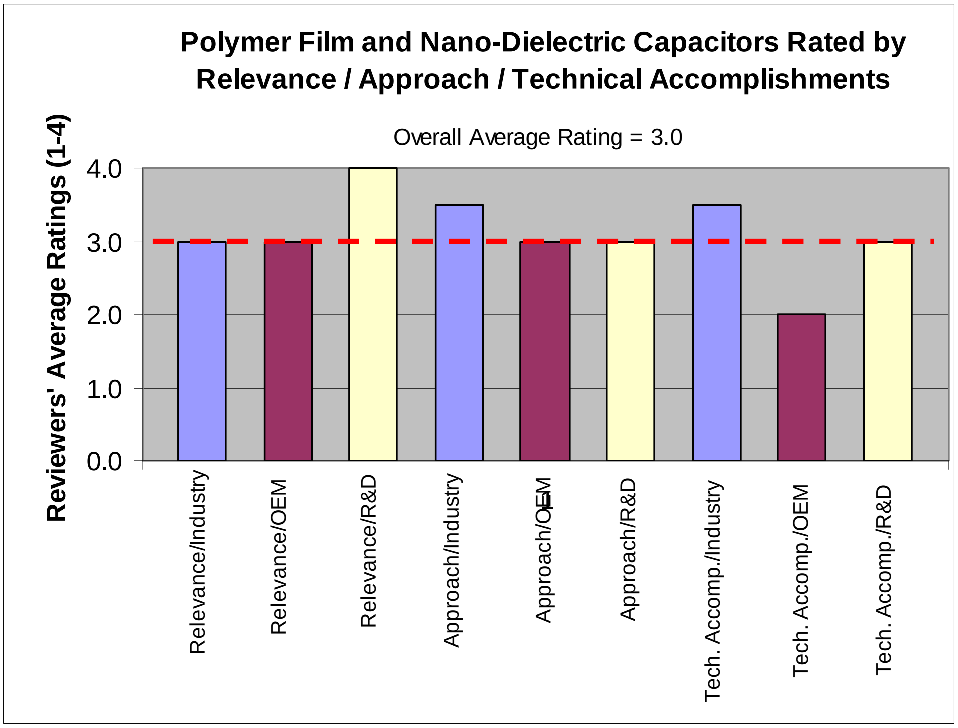
R&D Comments:

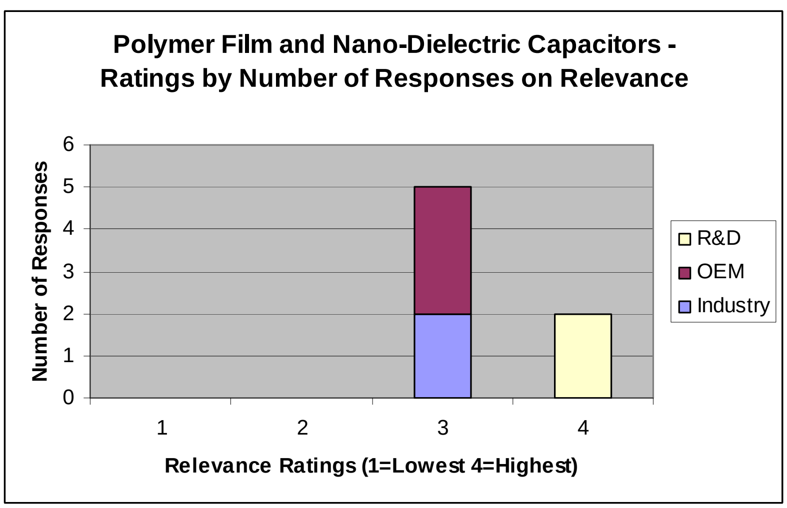
- Glass ceramics promise good reliability, power density and temperature stability
- Leveraging of commercial technology is clever and shows promise
- Concern is raised if cost target can be met with flat panel glass
- Benign failure mode discussion should be presented
- Development of commercial glass with good dielectric and reliability properties at high temperature is a major accomplishment
- Ability to scale up from low voltage computer application to high voltage automotive applications ability is a concern
- Material and electrical properties may not be suitable for vehicle environment; test plan is needed to address these issues

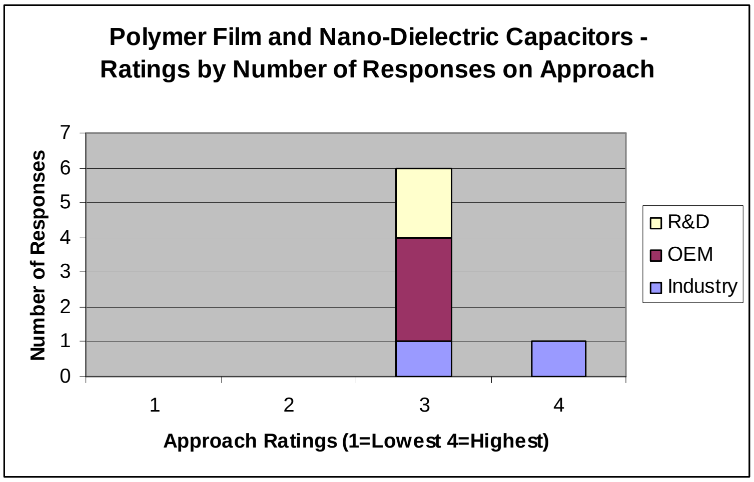
Polymer Film and Nanoceramic Dielectrics for DC Bus Capacitors
Bruce Tuttle – Sandia National Laboratory (SNL)

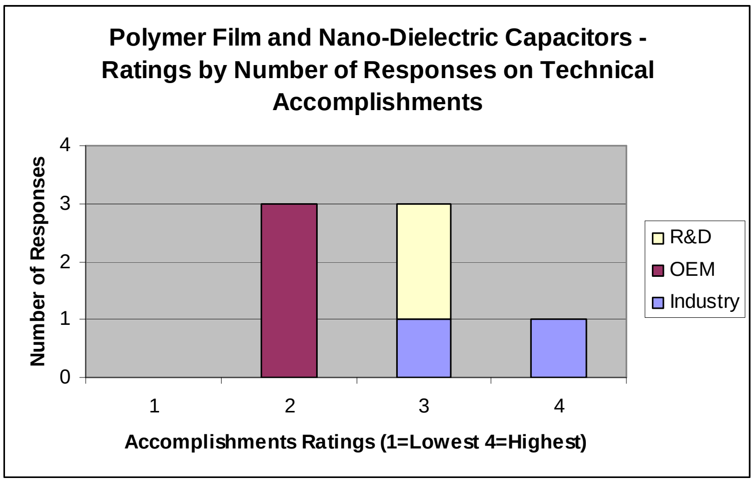
Project Summary: In FY06 both polymer-film capacitors and ceramic capacitors were pursued since each technology has the potential for large benefits but also face significant technical challenges. Polymer film capacitors can provide efficient ripple current protection at reasonable cost with graceful failure while ceramic capacitors can offer high energy density with volumetric and weight efficiency. Specifically, SNL investigated low cost norbornene polymer chemistry to produce polymer films with high dielectric constant, enhanced mechanical flexibility and superior high temperature electrical properties. In addition SNL explored multilayer nanoceramic dielectrics due to their high energy density over a wide range of operating temperatures with the potential for significant size reduction. High quality thin dielectric layers were fabricated. A collaboration was initiated with Honeywell FM&T as an industrial partner. In FY07 norbornene polymer films will be mechanically and electrically test. Chem-prep nanoceramic dielectrics will be developed with lower sintering temperatures and no porosity. High quality multilayer capacitors will be fabricated for electrical testing.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.


Polymer Film and Nano-Dielectric Capacitors Rated by Relevance / Approach / Technical Accomplishments
Overall Average Rating = 3.0
Reviewers' Average Ratings (1-4)
4.0
3.0
2.0
1.0
0.0
Relevance/Industry
Relevance/OEM
Relevance/R&D
Approach/Industry
Approach/OEM
Approach/R&D
Tech. Accomp./Industry
Tech. Accomp./OEM
Tech. Accomp./R&D


Polymer Film and Nano-Dielectric Capacitors - Ratings by Number of Responses on Relevance
Number of Responses
6
5
4
3
2
1
0
1
2
3
4
Relevance Ratings (1=Lowest 4=Highest)
R&D
OEM
Industry





<u>Industry Comments:</u>

- Good S&T effort but benefit to automotive applications questioned
- Concern in terms of approach since resources are split between two dielectrics
- Good project with sound program plan but need capacitor technology by 2009
- Incremental improvements but revolutionary advance in dielectric technology needed

<u>OEM Comments:</u>

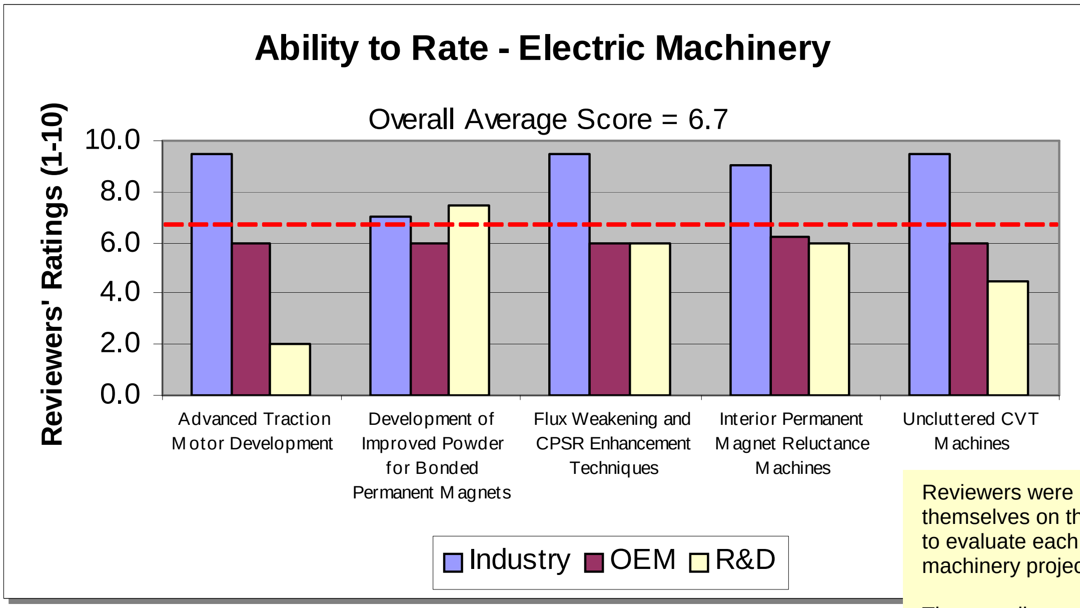
- High temperature tolerant. Low cost, easily manufactured capacitors are critical to US FreedomCAR so that OEMs can offer affordable, fully functional HEVs
- Approval for approach with decision points
- Further research needed to assess temperature capability of nanoceramic dielectrics

<u>R&D Comments:</u>

- Approval of two path approach with decision point needed for most promising approach in order to produce prototype capacitors for analytical testing
- Focus on nanoceramic dielectrics should be directed towards cost target and benign failure mode requirement
- Industrial partnering supported
- Scaling of nanoceramic capacitor to meet capacitance requirement could be a major issue

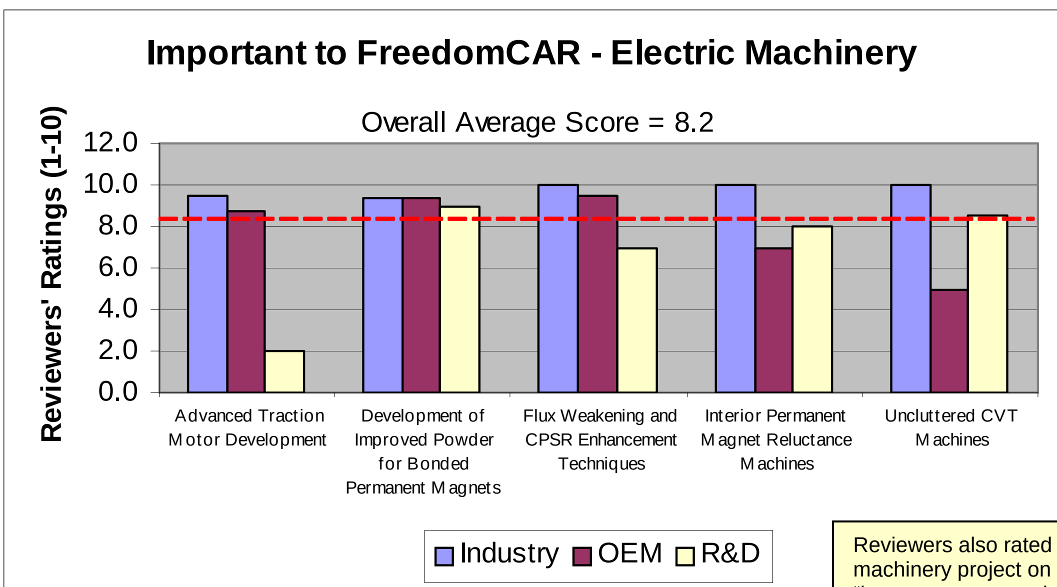
Summary of Project Evaluation Feedback for Electric Machinery

The following information provides summaries of the projects that were reviewed and their ratings.



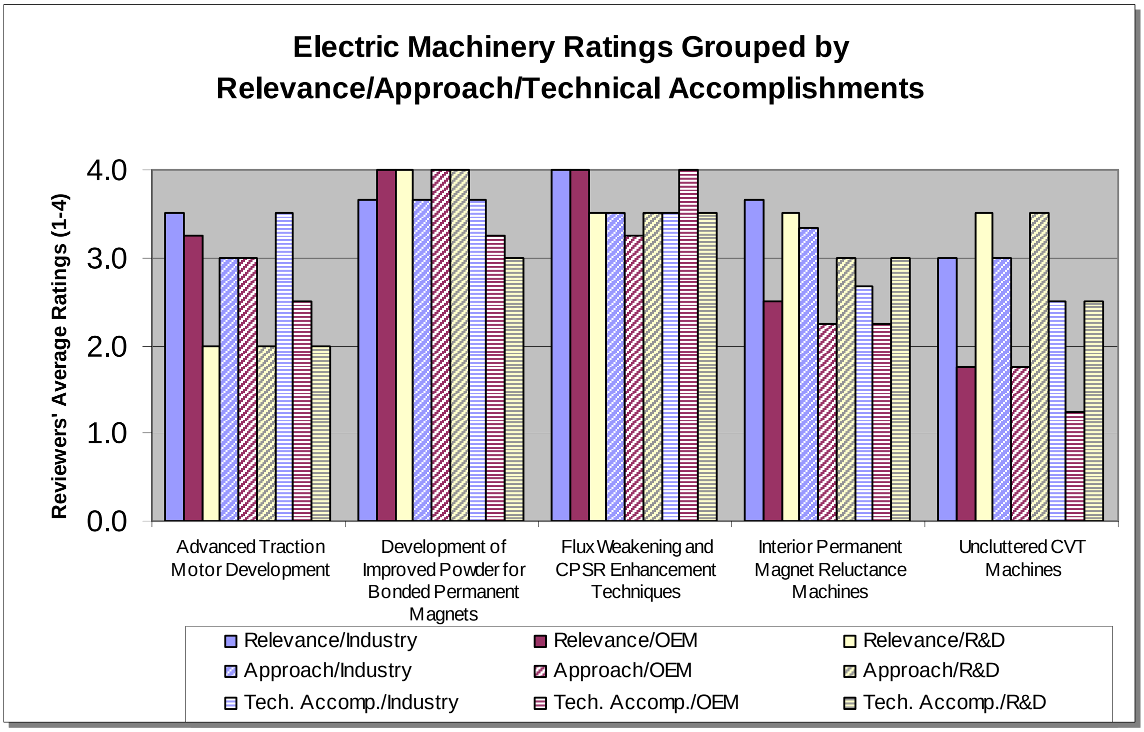
Reviewers were asked to rate themselves on their own ability to evaluate each electric machinery project.

The overall average of all the responses from all reviewers was 6.7/10. Responses ranged from 1 (lowest) to 10



Reviewers also rated each electric machinery project on its "importance to meeting FreedomCAR goals."

The overall average response from all projects and all reviewers was 8.2/10. Responses ranged from 1 (lowest) to 10 (highest).



Reviewers rated each electric machinery project on its "relevance," "approach," and "technical achievement."

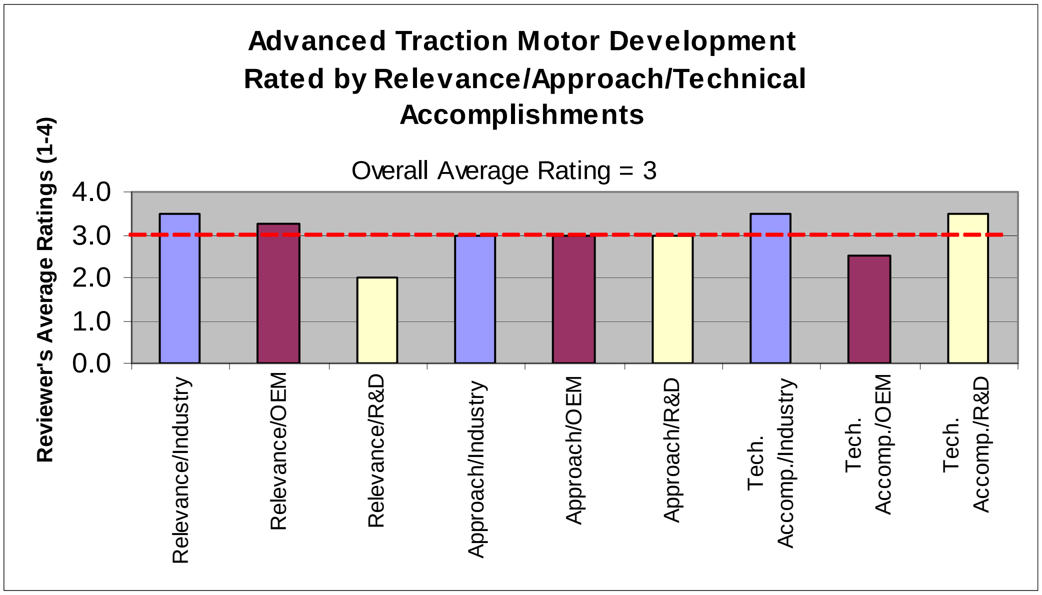
Responses ranged from 1 (lowest) to 4 (highest).

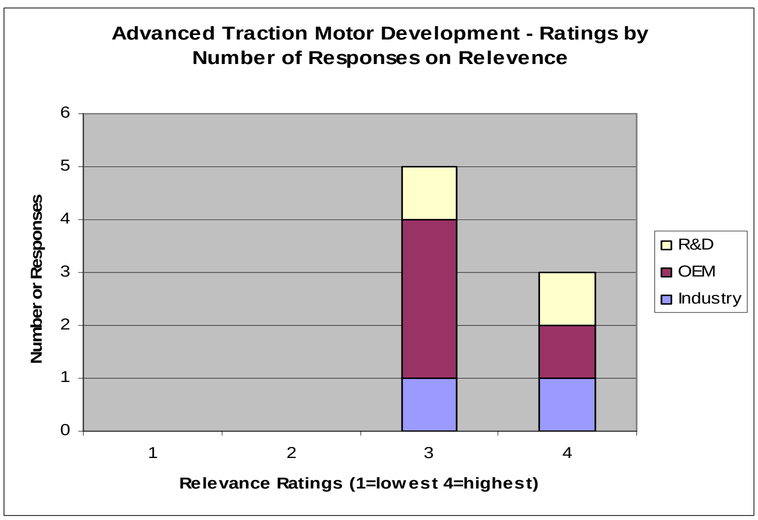
Summary of Project Evaluation Feedback for Specific Electric Machinery Projects

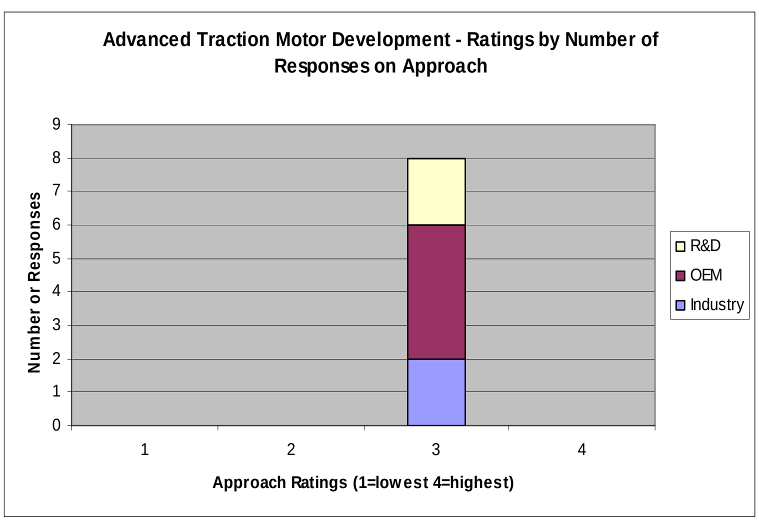
Advanced Traction Motor Development
Josh Ley - UQM

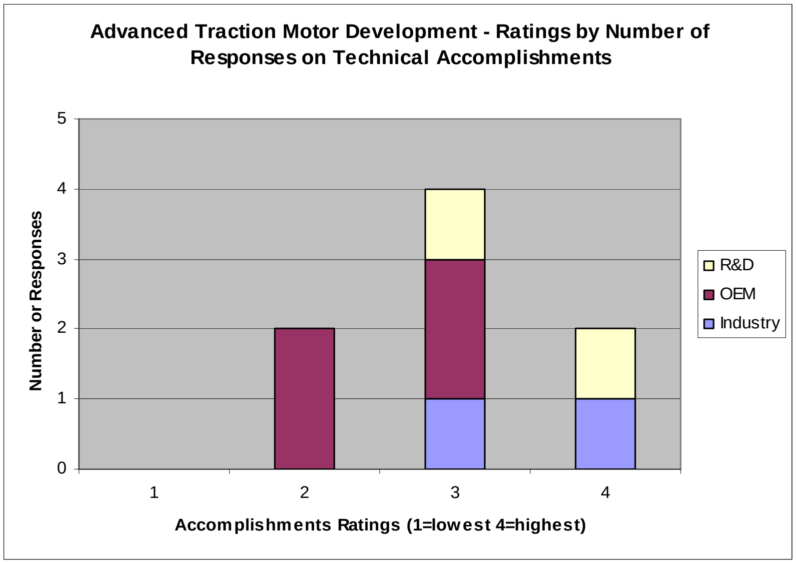
Project Summary: This effort was a one year project that evolved as a result of an RFP to industry. Phase I of this effort concluded with UQM delivering a report detailing three separate motor designs investigated for use as traction machines. They were given a detailed motor specification and after examining different topologies completed a through design of an IPM machine. As part of this effort they also completed a through cost projection of the selected motor topology.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.


Advanced Traction Motor Development
Rated by Relevance/Approach/Technical Accomplishments
Overall Average Rating = 3
Reviewer's Average Ratings (1-4)
4.0
3.0
2.0
1.0
0.0
Relevance/Industry
Relevance/OEM
Relevance/R&D
Approach/Industry
Approach/OEM
Approach/R&D
Tech. Accomp./Industry
Tech. Accomp./OEM
Tech. Accomp./R&D


Advanced Traction Motor Development - Ratings by Number of Responses on Relevence
Number or Responses
6
5
4
3
2
1
0
1
2
3
4
Relevance Ratings (1=lowest 4=highest)
R&D
OEM
Industry


Advanced Traction Motor Development - Ratings by Number of Responses on Approach
Number or Responses
9
8
7
6
5
4
3
2
1
0
1
2
3
4
Approach Ratings (1=lowest 4=highest)
R&D
OEM
Industry



Industry Comments:

- Not a real technical leap, relevant in that speeds are higher, like to see more stretch
- Solid progress and well thought out objectives, practical approach to achieving high performance at a reasonable cost
- Would like to see how other material choices would benefit the designs
- Questioned costing numbers
- Did not seem to sufficiently optimize tradeoffs of higher reluctance designs

OEM Comments:

- Good, useful analysis work, questioned cost analysis
- Need similar analysis of power electronics required
- Technical approach is good, research is very relevant to FC
- Experience of the PI in the supply base and in industry is good approach in the project
- Want more background cost details
- Need to address NVH

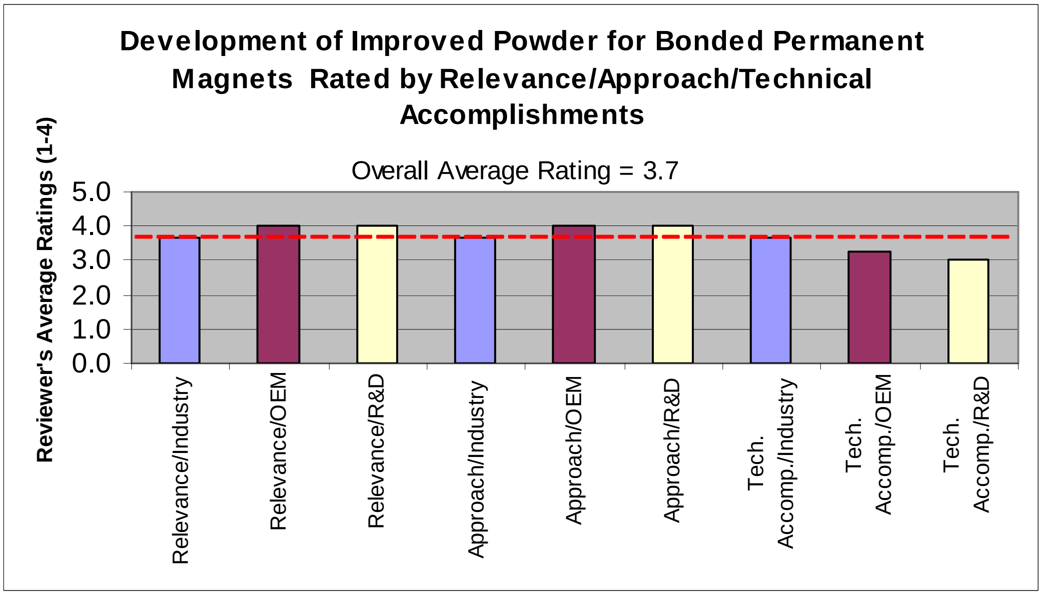
R&D Comments:

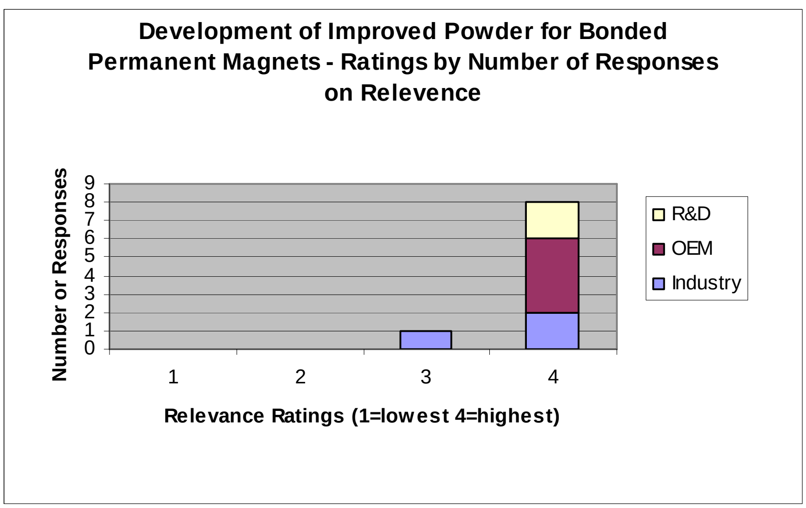
- Innovative motor design cuts cost and wt of magnet and improves specific power and power density
- Good simulations
- Conservative but conventional approach..just optimizing
- Wider CPSR is not addressed

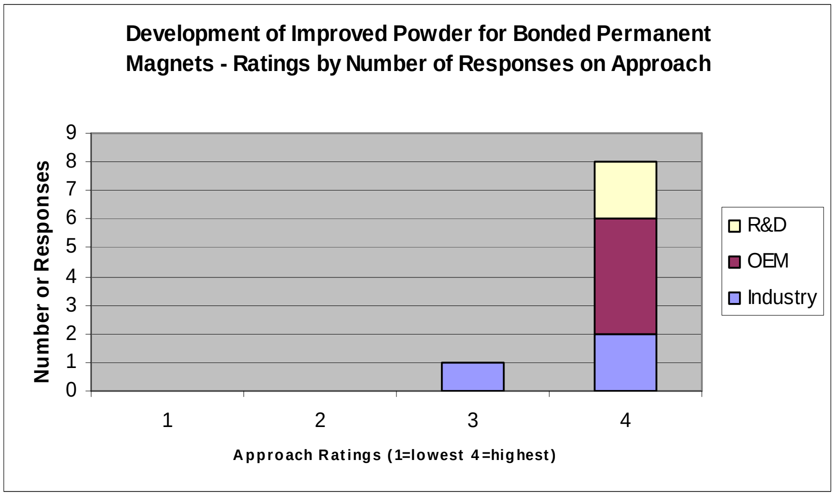
Development of Improved Powder for Bonded Permanent Magnets
Iver Anderson - Ames

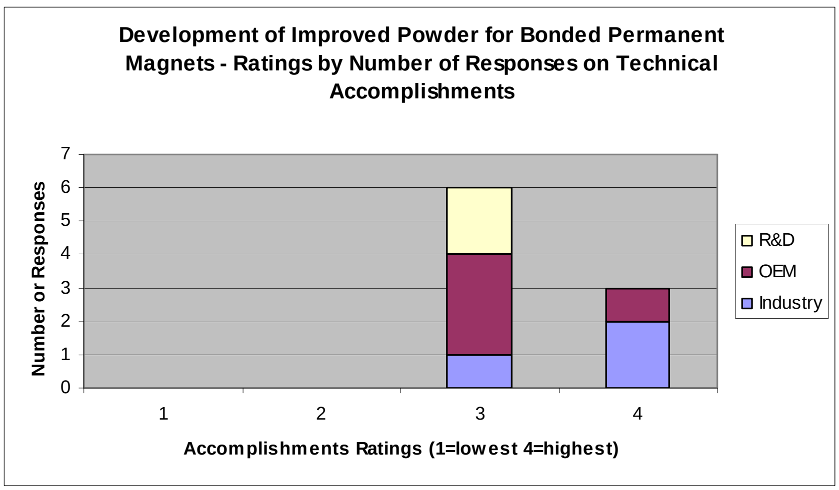
Project Summary: The work on bonded magnets at Ames was begun in FY01. Through the past few years they have worked on different alloys to enable higher temperature operation of bonded magnets for use in motor designs. They have also worked on developing methods for low cost manufacturing of the magnets to enable injection molding of the magnets into innovative interior motor designs.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.









<u>Industry Comments:</u>

- Impressive research group, cutting edge work, good work plan
- Need to push to commercialization
- Work helpful for cost reduction but maybe offset by torque density penalty
- Need to work with a motor manufacturer to evaluate impacts

<u>OEM Comments:</u>

- Research relevant to FCVT mission, good engineering work and results presented
- Has identified strong partners for collaboration
- Progress being made, but slower than would like
- Long term, high risk project

<u>R&D Comments:</u>

- Innovative material solutions
- Good process development shown
- Cost needs to be addressed
- Good research and results but needs to be tied to actual machine performance

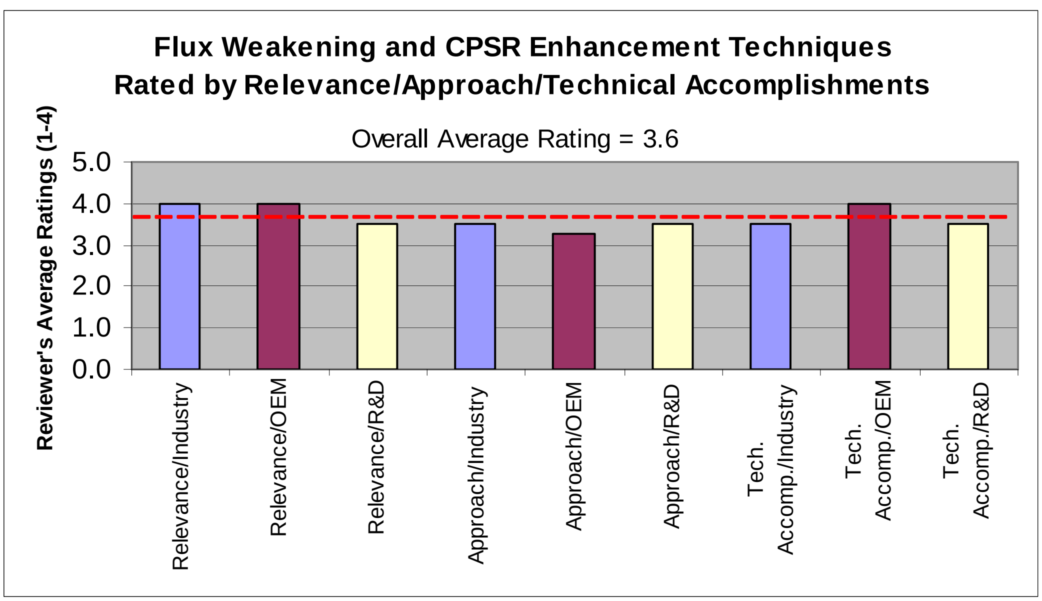
Flux Weakening and CPSR Enhancement Techniques
(Control of Fractional Slot Motors Made With Concentrated Windings and Extending the CPSR of Synchronous Reluctance Traction Drive Motor)
John McKeever - ORNL

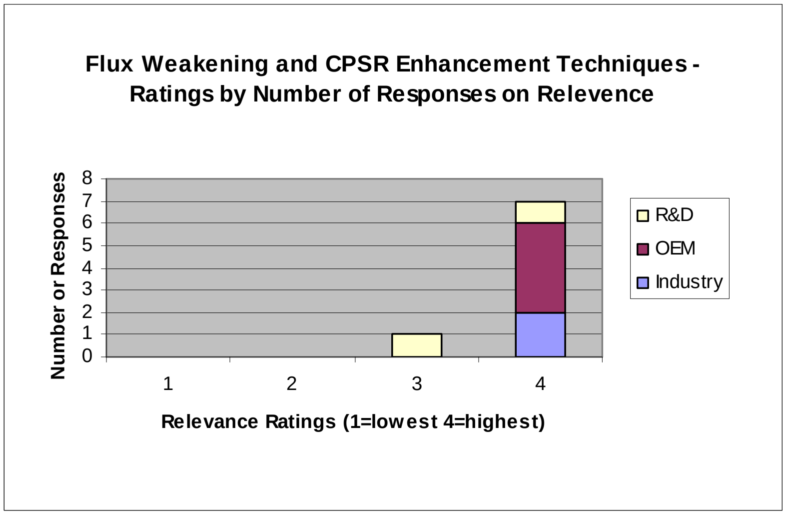
Project Summary: The Control of Fractional Slot Motors Made with Concentrated Windings and Extending the CPSR of Synchronous Reluctance Traction Drive Motor projects were presented together at the review.

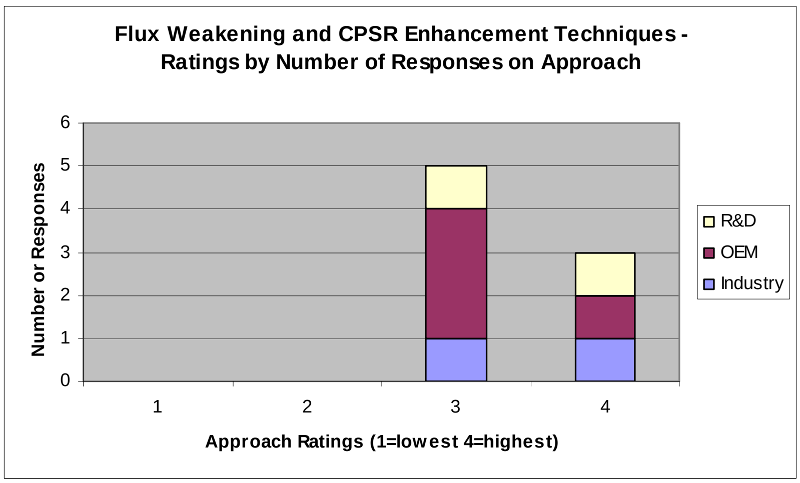
The Control of Fractional Slot Motors with Concentrated Windings project began in FY05 as collaboration with the University of Wisconsin (UW). UW designed and built a 6K rpm prototype motor utilizing concentrated windings. ORNL's role is to evaluate the motor and test its operation with two different control algorithms. One algorithm is a development from a subcontract with the University of Tennessee (UT) and will use an unconventional field weakening approach for improved efficiency, while a second algorithm being developed by UW will utilize a sensorless control method for a lower cost application.

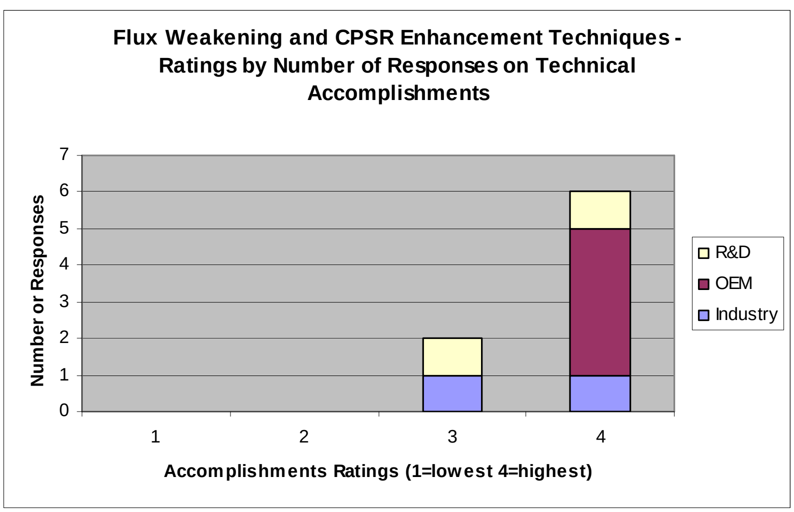
The Extending the CPSR of Synchronous Reluctance Traction Drive Motor project was a small effort that began in FY06 to reexamine the possibility of utilizing a synchronous reluctance (SR) motor as a traction machine. The project results were presented together at the review. Through modeling it was determined that, given the FreedomCAR targets, the cost advantages of not having permanent magnet material in the rotor appear to still be outweighed by the added weight and size of a pure SR motor and as such this project to utilize these motors for traction applications has been discontinued.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.




Flux Weakening and CPSR Enhancement Techniques - Ratings by Number of Responses on Relevence
Number or Responses
0
1
2
3
4
5
6
7
8
1
2
3
4
Relevance Ratings (1=lowest 4=highest)
R&D
OEM
Industry


Flux Weakening and CPSR Enhancement Techniques - Ratings by Number of Responses on Approach
Number or Responses
0
1
2
3
4
5
6
1
2
3
4
Approach Ratings (1=lowest 4=highest)
R&D
OEM
Industry


Flux Weakening and CPSR Enhancement Techniques - Ratings by Number of Responses on Technical Accomplishments
Number or Responses
0
1
2
3
4
5
6
7
1
2
3
4
Accomplishments Ratings (1=lowest 4=highest)
R&D
OEM
Industry

Control of Fractional Slot Motors Made With Concentrated Windings
Industry Comments:

- Technically sound approach, good collaboration with UW, addressed all technical targets
- ORNL strength..exploring novel machine types, good solid engineering work
- Novel machine
- Concern over core loss in rotor/stator

OEMs Comments:

- Flux weakening work very relevant to FCVT program and OEMs, attacks all the key issues facing FC, also provides detailed work valuable to OEMs
- One of the best project in APEEM, research stretches the state of knowledge about motors
- Solid engineering analysis

R&D Comments:

- Addresses many FC pathways and targets
- Cost may not meet target, but has been considered
- A design improvement, not innovation
- A strong team with experience in machine design, modeling, analysis, simulation and control
- Need to verify performance with full power model

Extending the CPSR of Synchronous Reluctance Traction Drive Motor
Industry Comments:

- SR work was disappointing

OEM Comments:

- Does not address the fundamental NVH issues

R&D Comments:

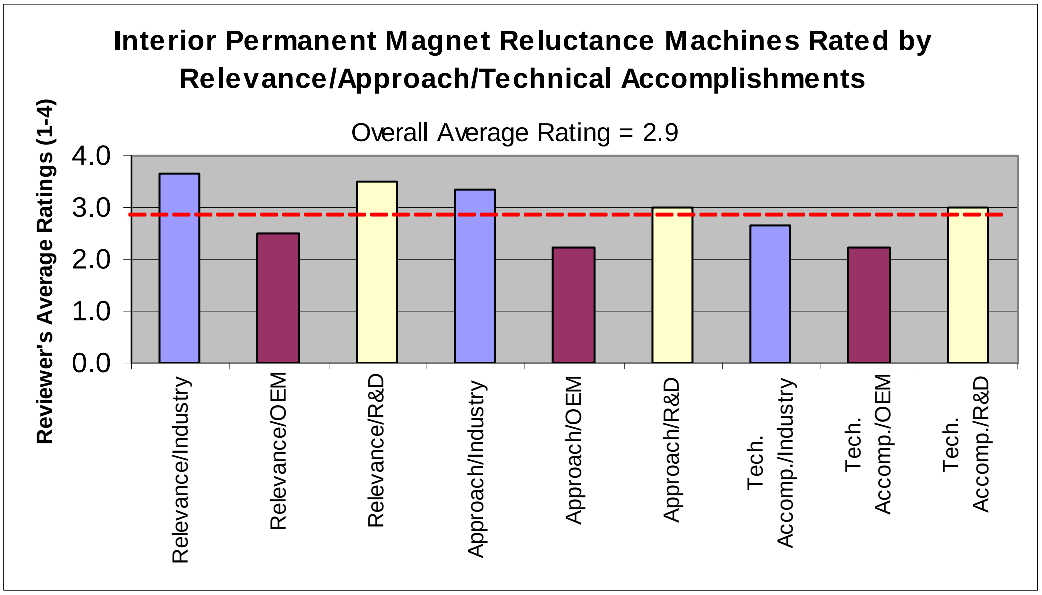
- Conducted sufficient assessment to eliminate SR traction motors from further consideration thus focusing further research

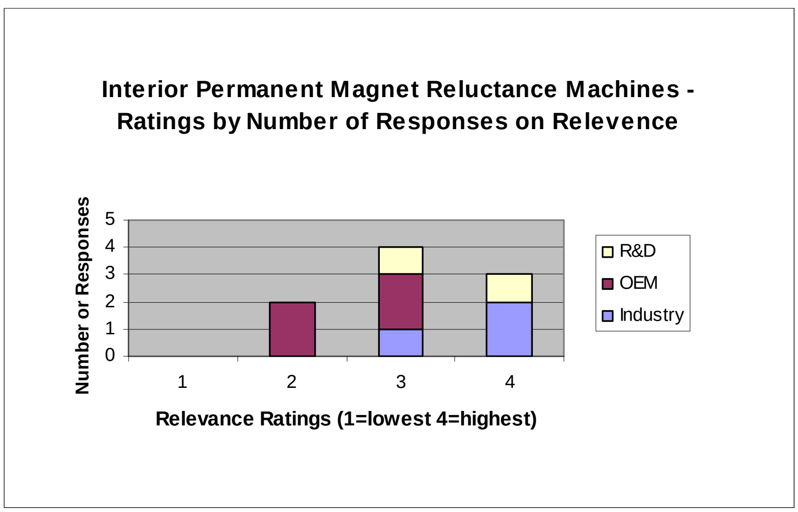
IPM Reluctance Machines
John Hsu-ORNL

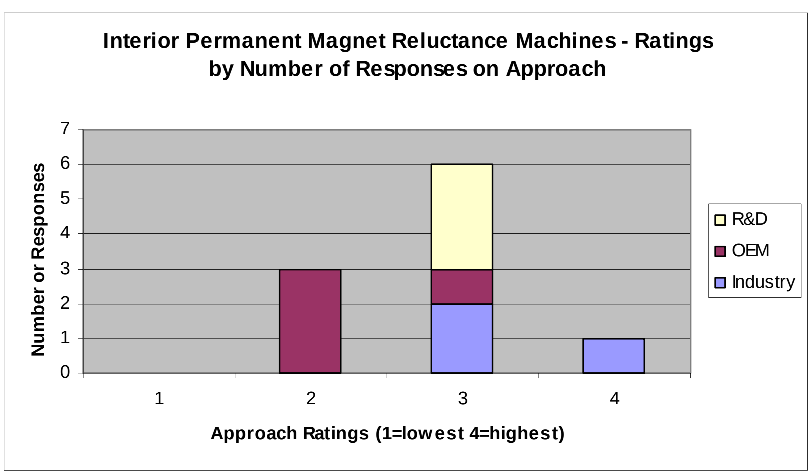
Project Summary: This presentation at the annual review consolidated two projects into one presentation. The 6K rpm RIPM machine and the 16K rpm BFE machine were presented together. Work on the 6K machine began in FY05 while the 16K project was begun in FY06. The 6K motor reported on this year is a radial gap IPM machine with side magnets. It does not include excitation coils. The 16K machine is a high speed motor with an entirely new rotor design incorporating external excitation coils.

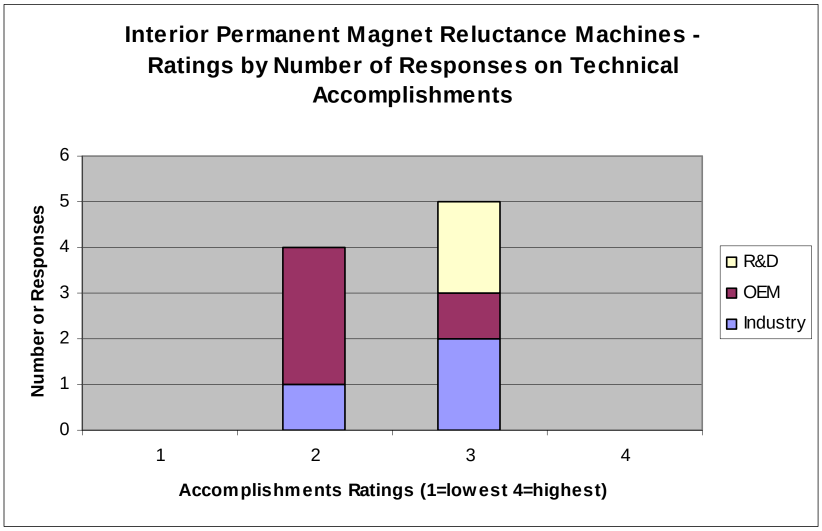
The 6K rpm motor is designed to be a drop in replacement for Prius type vehicle architectures (those using a DC to DC for a boost) with better performance. The 16K motor does not require a DC to DC converter and can achieve substantially reduced core losses at high speeds.

Charts summarizing reviewers’ ratings and reviewers’ comments are shown below.


Interior Permanent Magnet Reluctance Machines Rated by Relevance/Approach/Technical Accomplishments
Overall Average Rating = 2.9
Reviewer's Average Ratings (1-4)
4.0
3.0
2.0
1.0
0.0
Relevance/Industry
Relevance/OEM
Relevance/R&D
Approach/Industry
Approach/OEM
Approach/R&D
Tech. Accomp./Industry
Tech. Accomp./OEM
Tech. Accomp./R&D


Interior Permanent Magnet Reluctance Machines - Ratings by Number of Responses on Relevence
Number or Responses
5
4
3
2
1
0
1
2
3
4
Relevance Ratings (1=lowest 4=highest)
R&D
OEM
Industry


Interior Permanent Magnet Reluctance Machines - Ratings by Number of Responses on Approach
Number or Responses
7
6
5
4
3
2
1
0
1
2
3
4
Approach Ratings (1=lowest 4=highest)
R&D
OEM
Industry



<u>Industry Comments:</u>

- Considered 'innovative', 'creative', a design which 'pushes the envelope'
- Concern from one reviewer over ability to meet cost goals, thought design too complex
- Another reviewer felt concept was simple enough to implement and be practical with good potential to reduce costs
- Desire to see more validation data

<u>OEM Comments:</u>

- Feel design is too complicated
- Want to reserve opinion until see more data
- Concern over cost and reliability..ability to meet targets
- Recognize the design is innovative
- Presentation lacked background data, wanted to see some engineering analysis

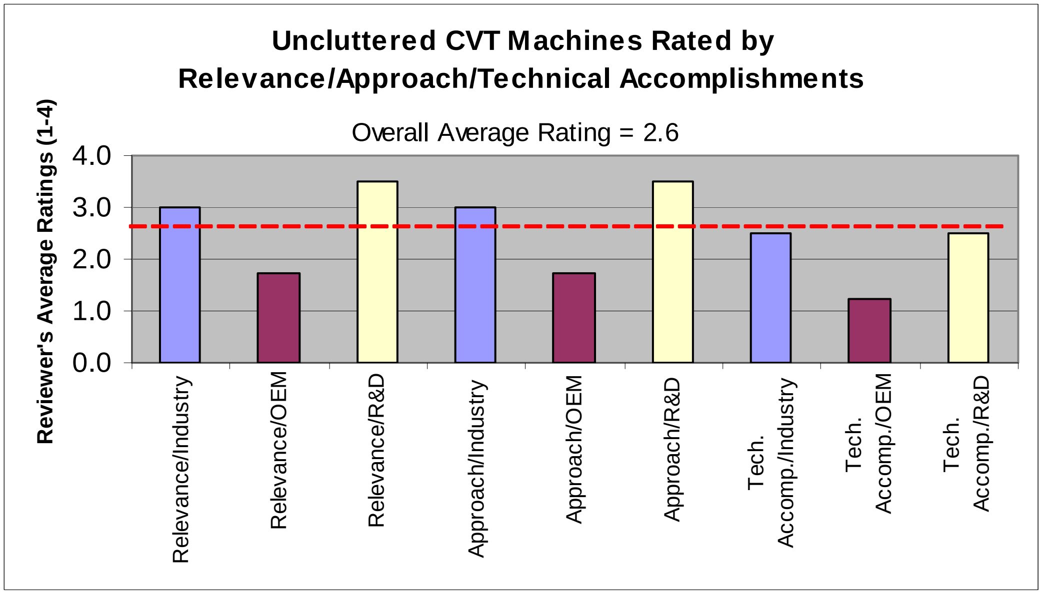
<u>R&D Comments:</u>

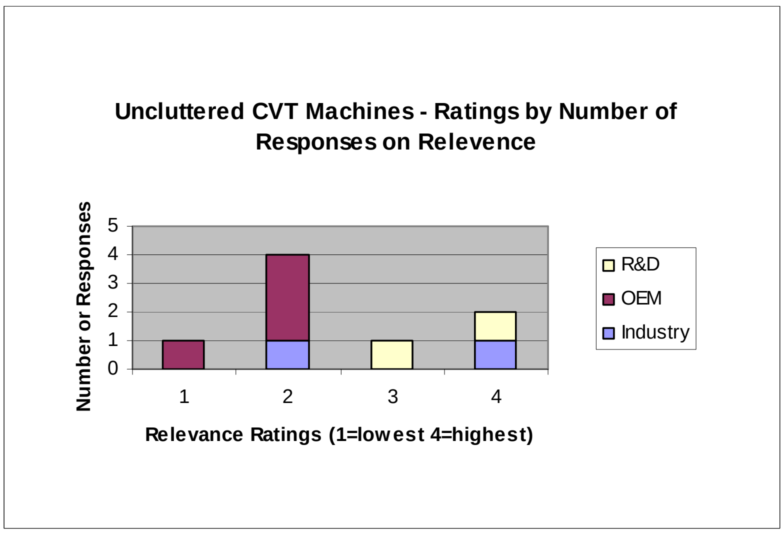
- Excellent mechanical stress study
- Feel should concentrate work on either the 6K or 16K motor
- Concept provides interesting motor improvements
- Desire comparisons with technologies other than the Prius

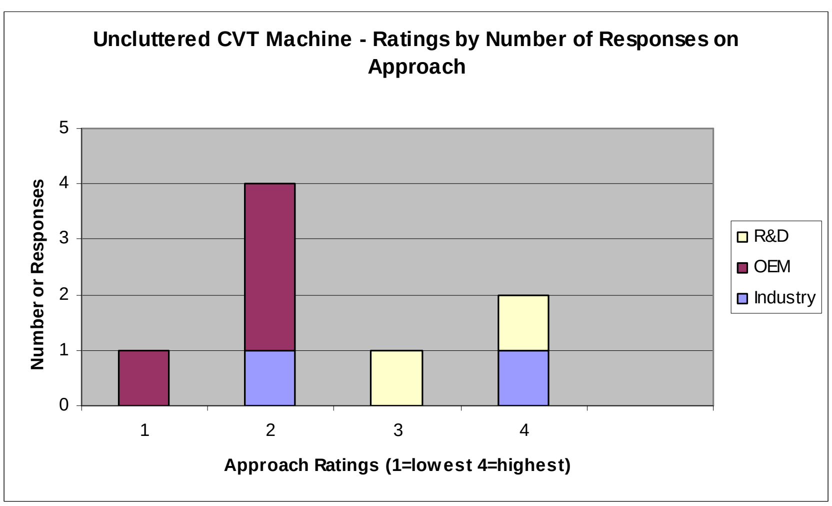
Uncluttered CVT Machine
John Hsu - ORNL

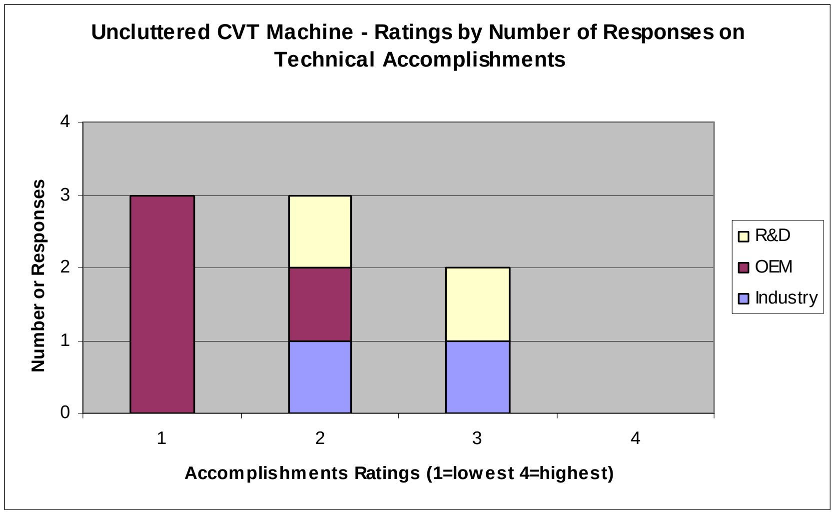
Project Summary: This project was officially begun in FY04, though significant effort wasn't allocated until FY05. The goal of this project is to combine the motor, generator and gearbox into one unit via a concept that will enable a doubling of the power density of current motor technologies. This project's success relies on the ability to realize an unconventional flux coupling mechanism. In FY06 the flux coupling mechanism was proven through a hardware prototype and in FY07 the complete motor/generator prototype will be fabricated.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.


Uncluttered CVT Machines Rated by Relevance/Approach/Technical Accomplishments
Overall Average Rating = 2.6
Reviewer's Average Ratings (1-4)
4.0
3.0
2.0
1.0
0.0
Relevance/Industry
Relevance/OEM
Relevance/R&D
Approach/Industry
Approach/OEM
Approach/R&D
Tech. Accomp./Industry
Tech. Accomp./OEM
Tech. Accomp./R&D


Uncluttered CVT Machines - Ratings by Number of Responses on Relevence
Number or Responses
5
4
3
2
1
0
1
2
3
4
Relevance Ratings (1=lowest 4=highest)
R&D
OEM
Industry


Uncluttered CVT Machine - Ratings by Number of Responses on Approach
Number or Responses
5
4
3
2
1
0
1
2
3
4
Approach Ratings (1=lowest 4=highest)
R&D
OEM
Industry



Industry Comments:

- A ‘stretch’ project, poses risks
- Needs more validation data
- Good approach
- Seems to miss the target of cost effectiveness
- Adding complexity to the system—higher cost, lower reliability issues

OEM Comments:

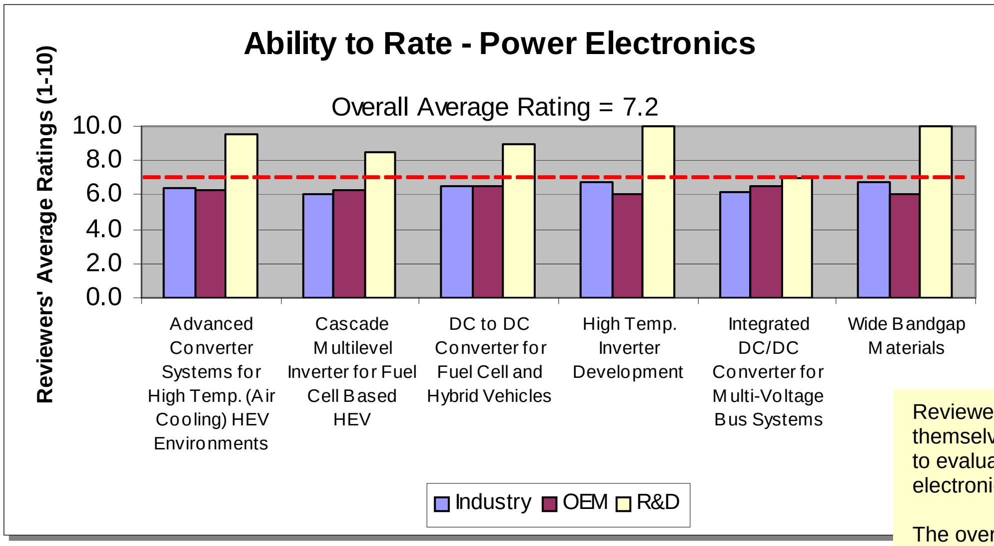
- Want realistic performance metrics
- Want to see data on hardware
- Too complex
- System impacts need to be communicated
- ‘innovative’, but likely impractical as OEMs want the ability to define their own system
- Can’t identify which targets the project design addresses

R&D Comments:

- Very ‘innovative’, good approach for meeting power/volume/wt goals
- ‘interesting’ design idea
- ‘unconventional’ approach
- Needs more attention to system level performance
- Needs to include control and power electronics in project scope

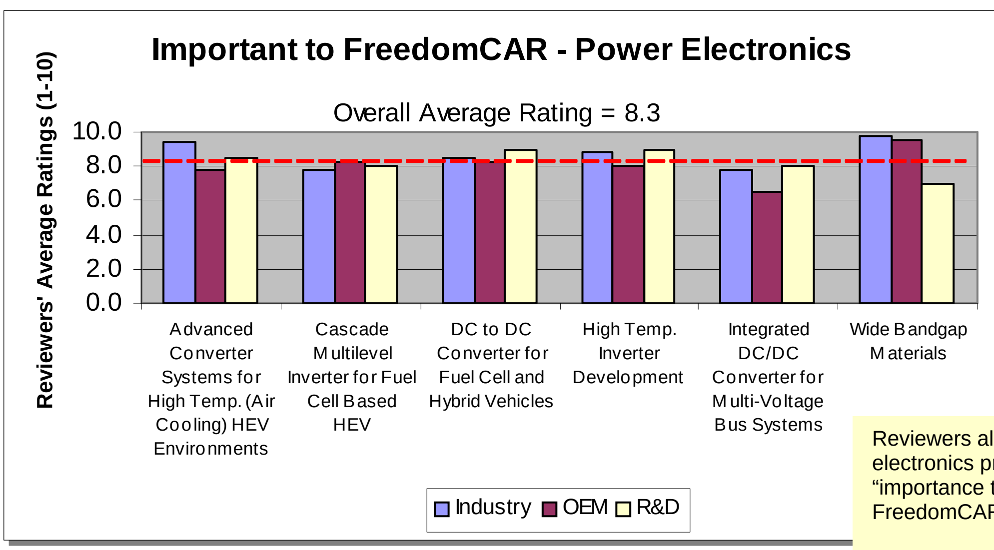
Summary of Project Evaluation Feedback for Power Electronics

The following information provides summaries of the projects that were reviewed and their ratings.



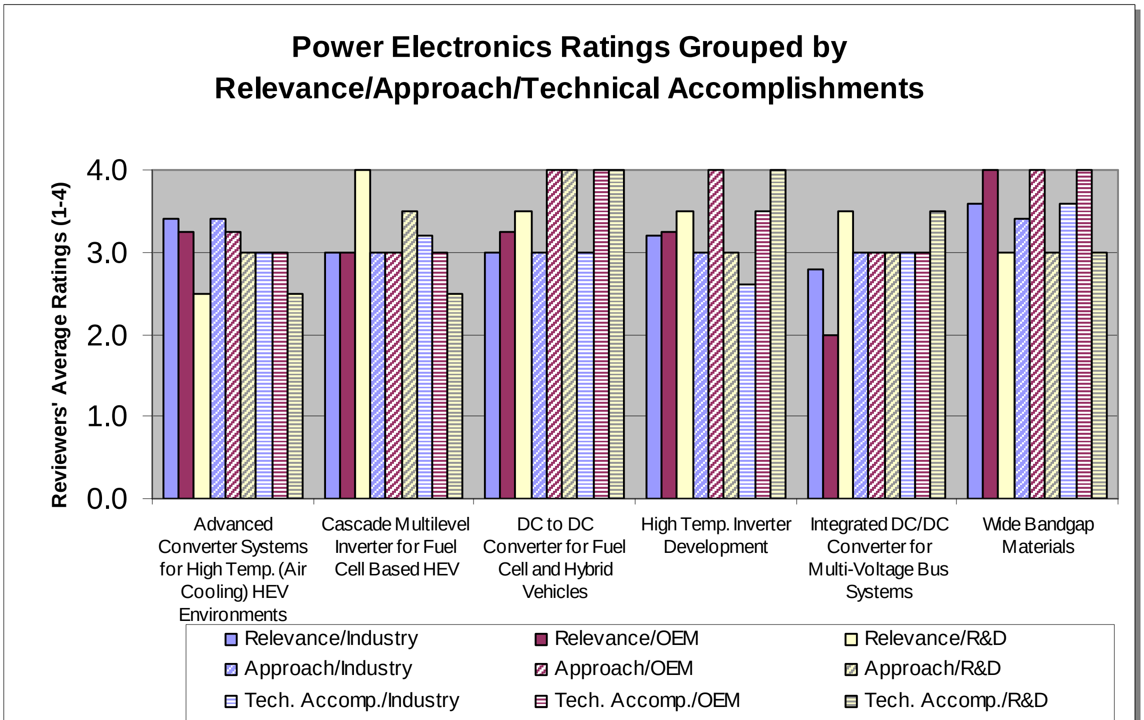
Reviewers were asked to rate themselves on their own ability to evaluate each power electronics project.

The overall average of all the responses from all reviewers was 7.2/10. Responses ranged from 1 (lowest) to 10 (highest).



Reviewers also rated each power electronics project on its "importance to meeting FreedomCAR goals."

The overall average response from all projects and all reviewers was 8.3/10. Responses ranged from 1 (lowest) to 10 (highest).



Reviewers rated each power electronics project on its "relevance," "approach," and "technical achievement."

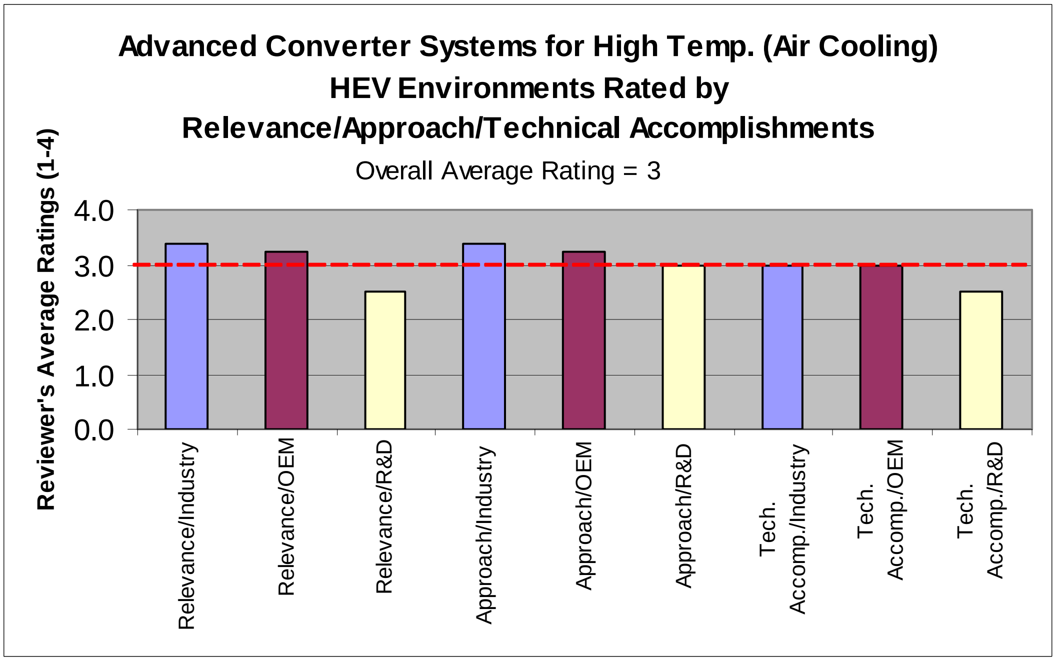
Responses ranged from 1 (lowest) to 4 (highest).

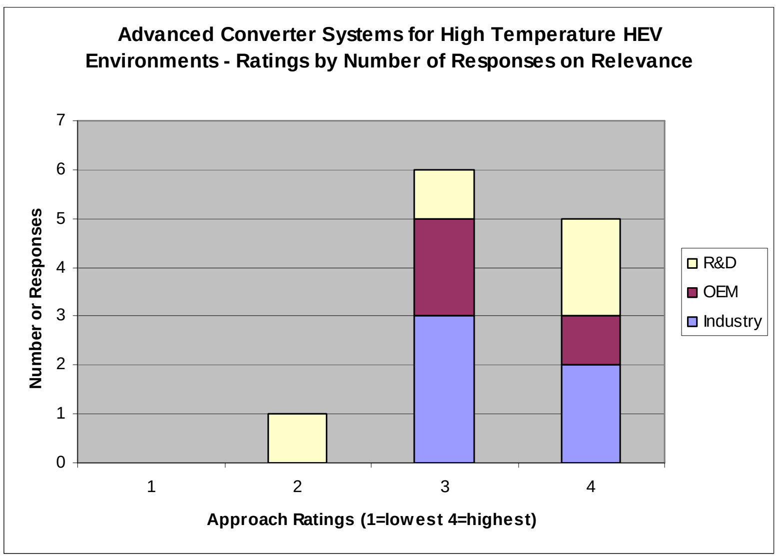
Summary of Project Evaluation Feedback for Specific Power Electronics Projects

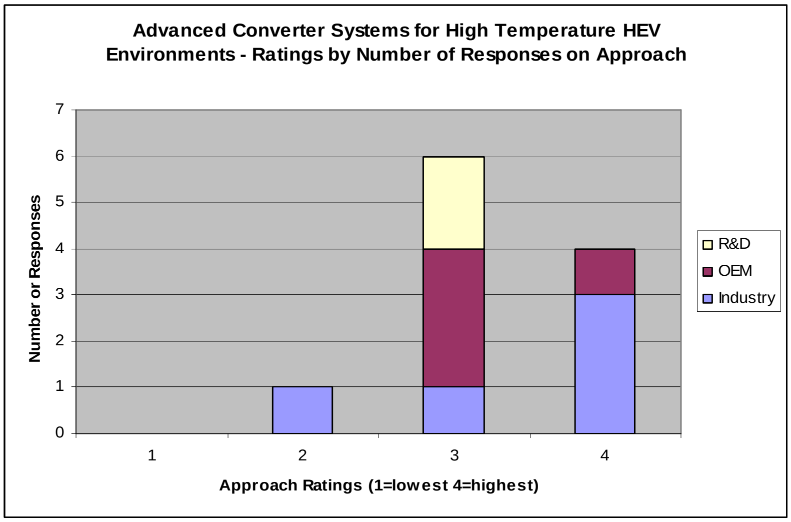
Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments
Leon Tolbert - ORNL

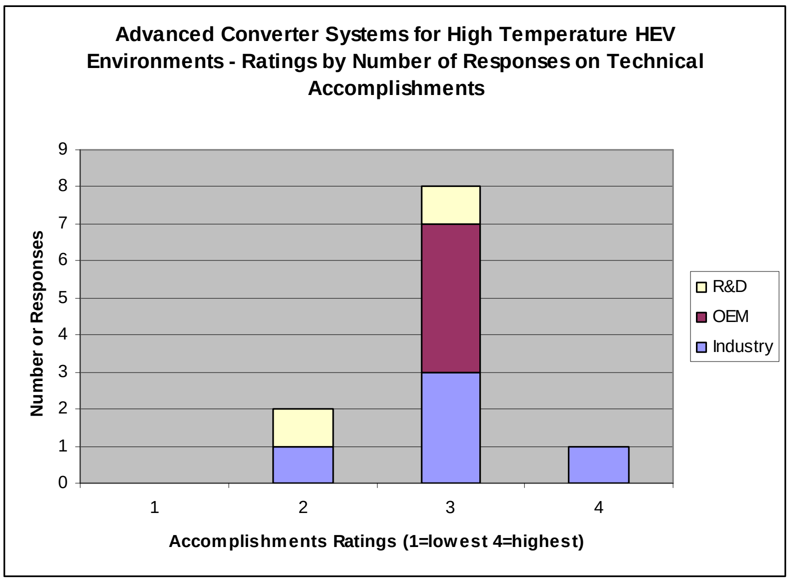
Project Summary: FY06 was the first year for this project. This is a modularized topology for a high temperature bidirectional DC to DC converter. It uses SiC switches, a SOI gate driver and high temp capacitors. Leon is teaming with MS for the design topology, UT for the development of the SOI gate driver, and Penn State for some capacitor evaluations. In FY07 the packaging work with UA, done under the WBG project in FY06 will be utilized in this project. The topology eliminates the magnetics normally associated with DC to DC converters and allows the battery pack to be subdivided into smaller modules for fault tolerance and redundancy.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.


Advanced Converter Systems for High Temp. (Air Cooling) HEV Environments Rated by Relevance/Approach/Technical Accomplishments
Overall Average Rating = 3
Reviewer's Average Ratings (1-4)
4.0
3.0
2.0
1.0
0.0
Relevance/Industry
Relevance/OEM
Relevance/R&D
Approach/Industry
Approach/OEM
Approach/R&D
Tech. Accomp./Industry
Tech. Accomp./OEM
Tech. Accomp./R&D


Advanced Converter Systems for High Temperature HEV Environments - Ratings by Number of Responses on Relevance
Number or Responses
7
6
5
4
3
2
1
0
1
2
3
4
Approach Ratings (1=lowest 4=highest)
R&D
OEM
Industry





Industry Comments:

- Benefit of project questioned-eliminating magnetics but replacing with caps...which is cheaper?
- Challenge to high temperature caps may diminish any positive accomplishment
- Innovative design with fault tolerance and redundancy, modular approach, good
- Need more info on performance data-component drift with temp and aging, wear out mechanism? Issues w/DC life on caps?
- Not sure how necessary to go magnetic free-but worth considering and documenting

OEM Comments:

- High temp gate driver work is needed
- Too much complexity w/battery
- Battery replacement cost needs to be considered
- Unusual approach that shifts burden from PE to battery (cost, reliability), need to considered added risk to battery-need to take system approach

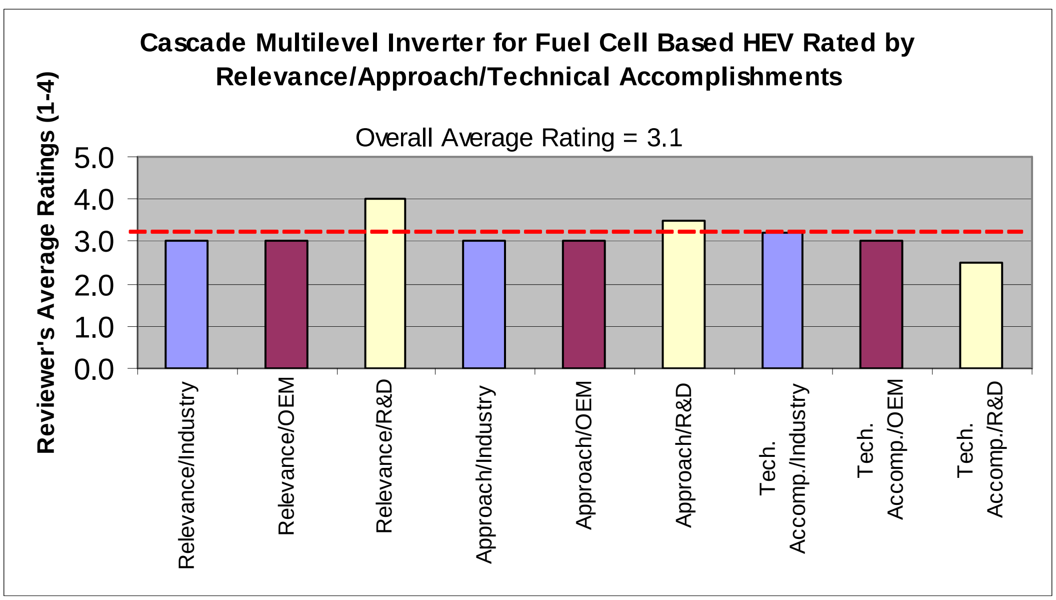
- Work on gate driver and high temp caps worthwhile and relevant to program

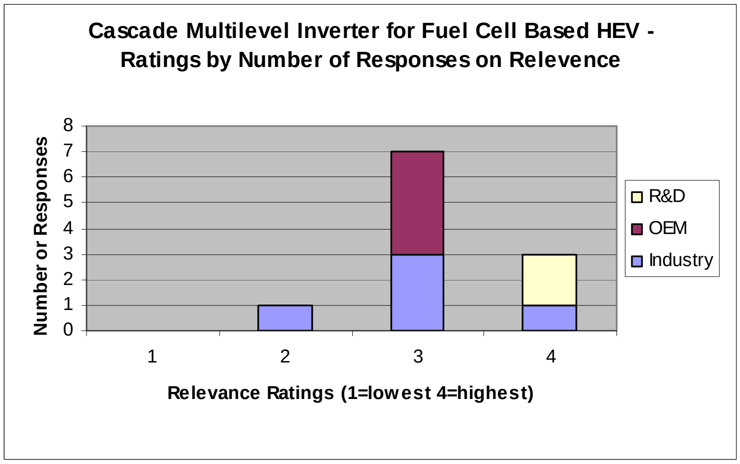
R&D Comments:
- Combines advantages of new design w/high temp devices to achieve FC goals at reasonable estimated costs
- Project risk is availability, quality, reliability of high temp components
- Need significant emphasis on reliable high temp packaging, questionable high power operation due to component losses in high current switching
- Goal is not practical, target high temp without considerations on loss dissipation but may provide answers to OEMs why SiC is not practical for 5-10 years

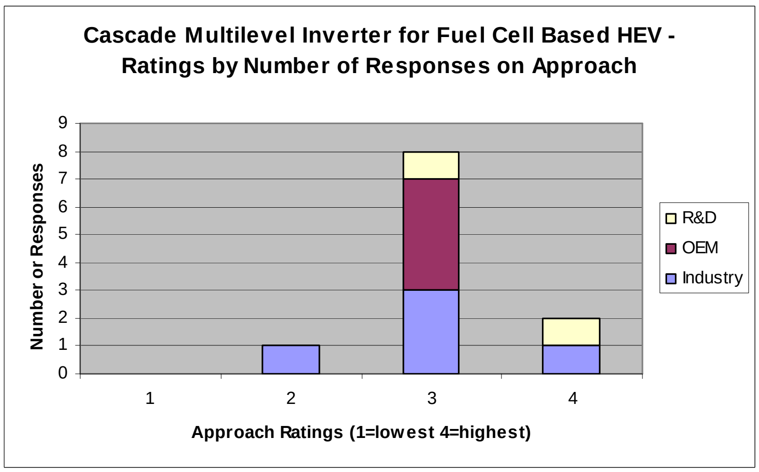
Cascade Multilevel Inverter for Fuel Cells
Burak Ozpineci - ORNL

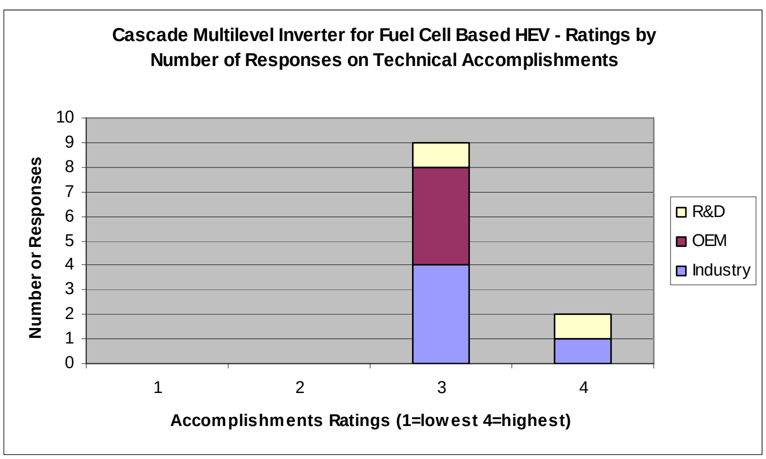
Project Summary: This project began in FY06 and the goal is to simulate, design and build a multilevel inverter to boost the voltage from a fuel cell stack and convert it to a 3 phase voltage output to drive a motor without the need for any magnetics. FY06 involved simulations and design. In FY07 and FY08 the unit will be built and tested.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.









<u>Industry Comments:</u>

- Cost tradeoffs not documented, is it cost effective to use Si to replace transformers?
- Need overall system benefits evaluation
- Novel technology with lots of degrees of freedom for control
- Need to take careful look at system effects of having multiple power sources, floating sources and cabling requirement

- Cascade multilevel inverters are most applicable to higher voltage drives, adds to much complexity
- Good simulation and modeling approach
- Design trade of increased switches and resulting control complexity is a serious issue.

OEM Comments:

- Adds cost and complexity
- Not matured enough project to evaluate
- Too early in the project to evaluate, approach is reasonable
- Design is complex and may prove to be costly, difficult to see how this can result in reduced costs but the design is intriguing enough to continue work and develop hardware to evaluate

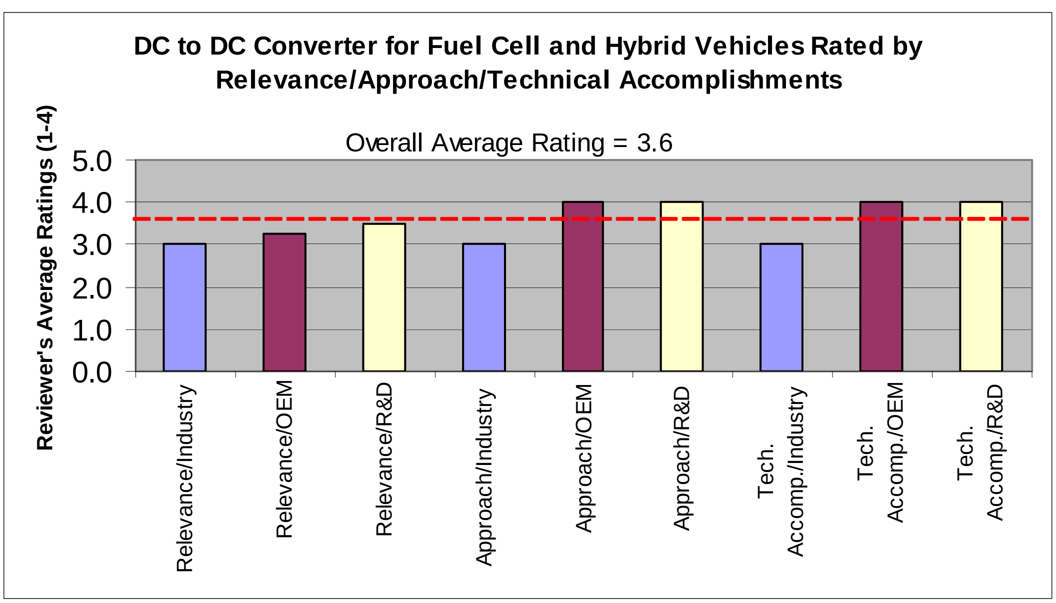
R&D Comments:

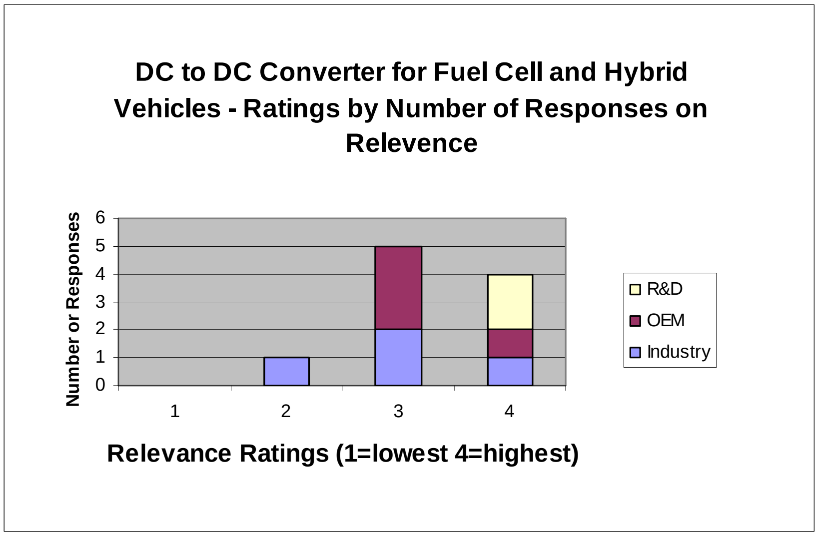
- 'very exciting' project, could integrate well with WBG work
- Characterization work is excellent and shows advantages of the approach
- Excellent , innovative design
- Not clear if the design can be accepted for traction drive but worthy of pursuing
- Need to study charge balancing, especially for drive cycle design consideration
- Still in conceptual stage, need substantial effort in control and design optimization
- No controller implementation is done to convince audience its feasibility

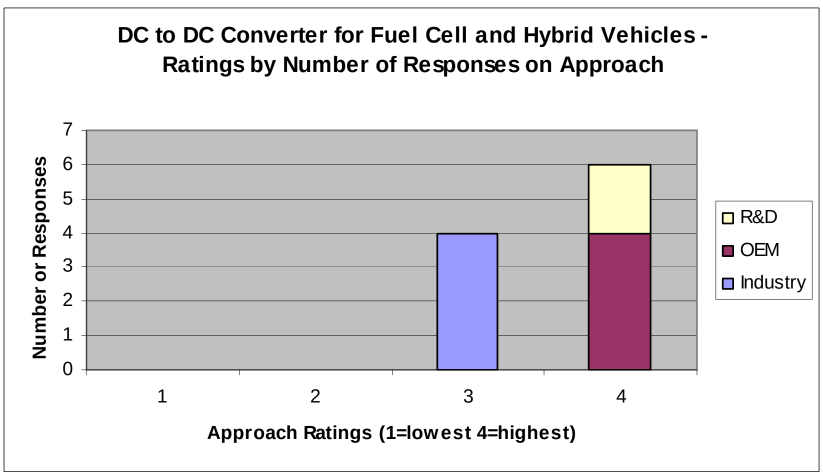
DC to DC Converter for Fuel Cell and Hybrid Vehicles
Lizhi Zhu - Ballard

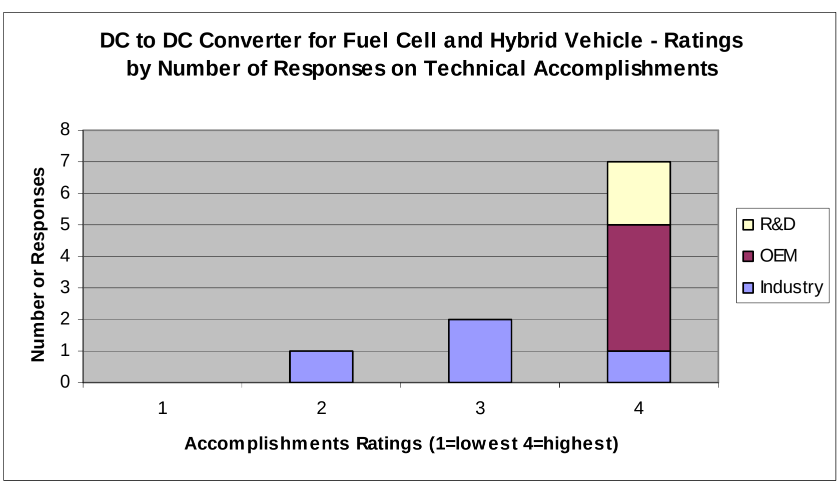
Project Summary: This effort began in FY04 as a subcontract from ORNL to industry via an RFP. It will be concluding this year with testing of their production high temperature step down DC to DC converter unit. Ballard has done extensive work in developing packaging improvements to meet the DOE targets given to them for this effort. The most demanding goal involved the cost target of $75/kW which the final unit will fall short of achieving.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.




DC to DC Converter for Fuel Cell and Hybrid Vehicles - Ratings by Number of Responses on Relevence
Number or Responses
0
1
2
3
4
5
6
1
2
3
4
Relevance Ratings (1=lowest 4=highest)
R&D
OEM
Industry


DC to DC Converter for Fuel Cell and Hybrid Vehicles - Ratings by Number of Responses on Approach
Number or Responses
0
1
2
3
4
5
6
7
1
2
3
4
Approach Ratings (1=lowest 4=highest)
R&D
OEM
Industry


DC to DC Converter for Fuel Cell and Hybrid Vehicle - Ratings by Number of Responses on Technical Accomplishments
Number or Responses
0
1
2
3
4
5
6
7
8
1
2
3
4
Accomplishments Ratings (1=lowest 4=highest)
R&D
OEM
Industry

Industry Comments:
- Concern that goals are changing and this technology may not be applicable in future (meets targets at 90°C but can meet at 105°C?)
- Good progress from first generation to second
- Consideration of manufacturing issues with costs good, appropriate focus on thermal requirements and influence on material usage
- Primarily technology demonstration, not innovative
- Engineering goals proceeding OK, technology goals lagging

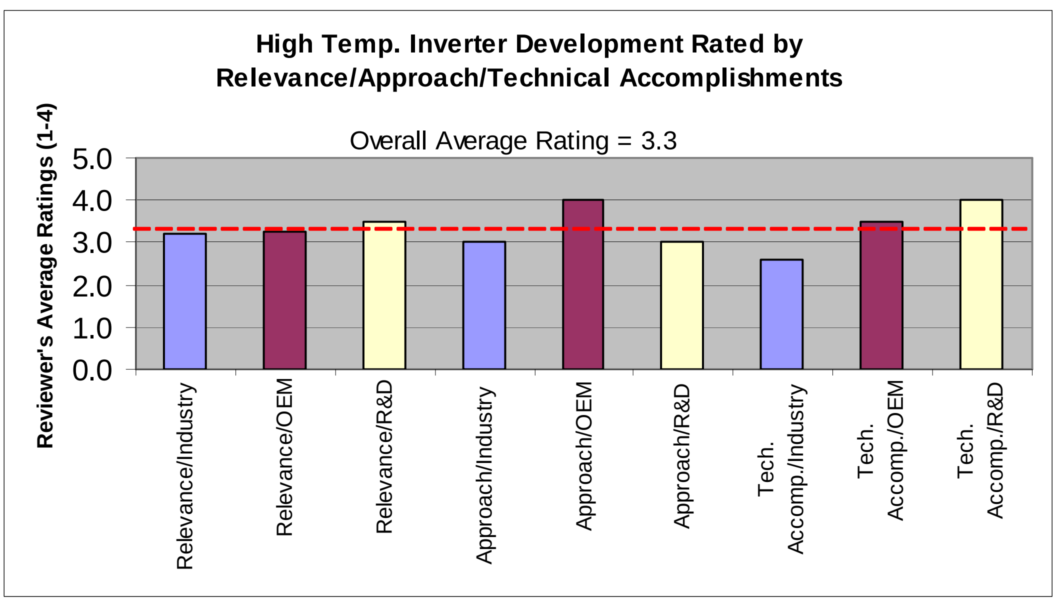
OEM Comments:
- Good engineering project with several innovative ideas
- Good methodical approach with good balance of technical advancement with practical reality

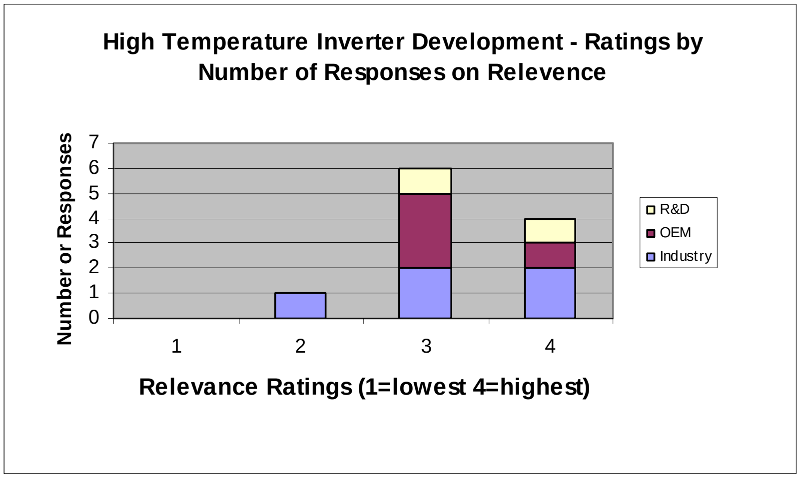
R&D Comments:
- Excellent beta design, still need to do some cost and weight reduction to meet DOE goals
- Work is very thorough

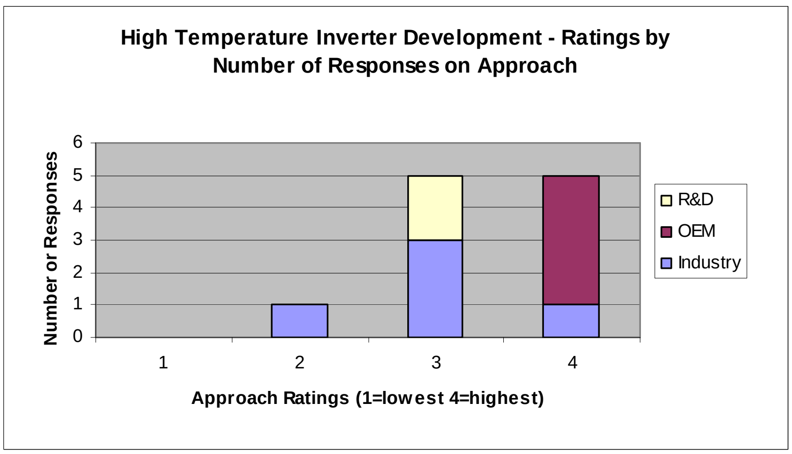
High Temperature Inverter Development
John Mooken - Semikron

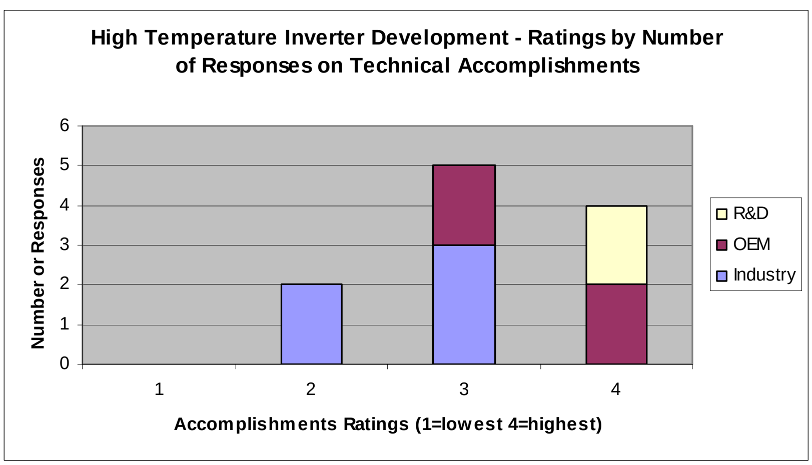
Project Summary: This project is the culmination of the original Semikron AIPM work which was extended to try to adapt the Semikron inverter for 105C coolant operation. The project was tasked with examinations of die attach mechanisms for high temperature and reliable operation. It also evaluated plastics, solders, current sensors, connectors, packaging, and device issues. During the course of the project Semikron determined that there was not a business case they could make for completing the project as the capacitors were not cost effective to realize the targets given them.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.









Industry Comments:

- Does not meet cost target, technology stretch not great enough
- Not innovative enough to make breakthroughs
- Returning funding and giving up on finding something better than 3X cost of caps is not impressive

- Very practical approach, project provides valuable info on packaging and associated reliability and cost---good reality check

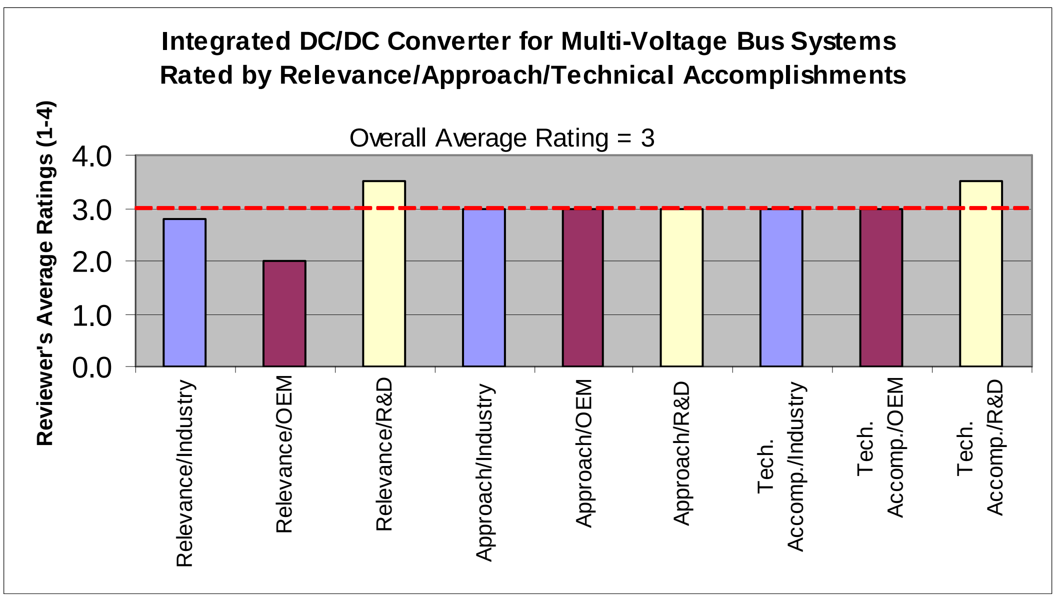
OEM Comments:
- Practical approach to research that considers manufacturability
- Semikron brings a practical businesslike perspective to the research

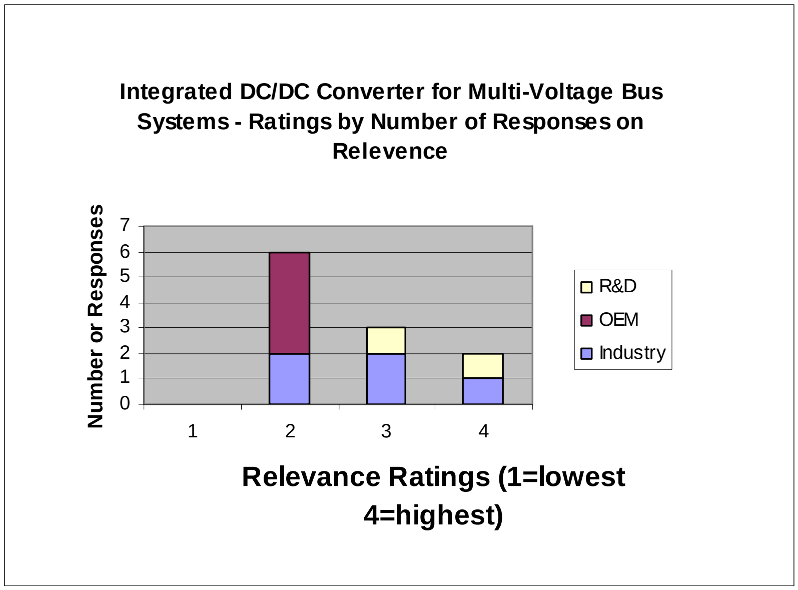
R&D Comments:
- Not high risk or long range
- Focus on reliability was good
- Good integration but presents significant problems with high temp cap and current sensors

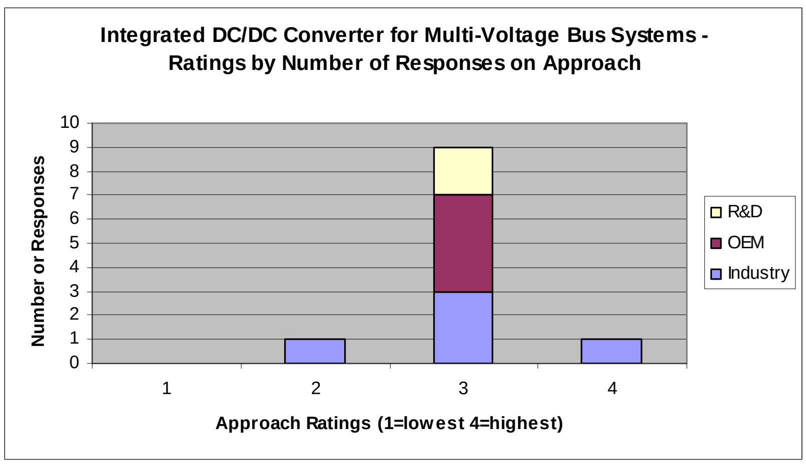
Integrated DC/DC Converter for Multiple Voltage Bus Systems
Gui-Jia Su - ORNL

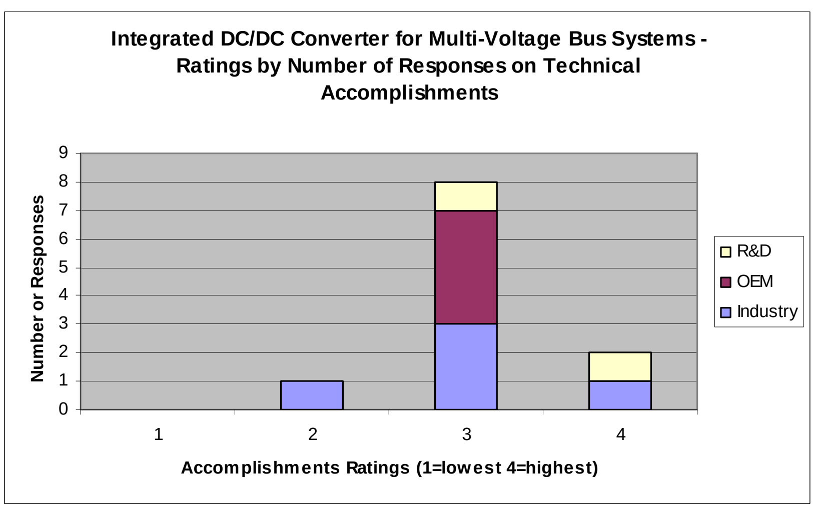
Project Summary: This project began in FY05. A prototype has been developed and tested successfully in FY06 demonstrating the ability to transfer power between 14 V, 42 V and a high voltage bus. The converter incorporates three DC to DC converters into a single modularized component. The increasing electrification of advanced vehicles will necessitate the increasing use of DC to DC converters. In FY07 the project will focus on assessing the dynamic responses of the converter and incorporate ultracapacitors to improve the controller response. This converter can readily be adapted to high temperature operation by substituting SiC devices.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.




Integrated DC/DC Converter for Multi-Voltage Bus Systems - Ratings by Number of Responses on Relevence
Number or Responses
0
1
2
3
4
5
6
7
1
2
3
4
R&D
OEM
Industry
Relevance Ratings (1=lowest 4=highest)


Integrated DC/DC Converter for Multi-Voltage Bus Systems - Ratings by Number of Responses on Approach
Number or Responses
0
1
2
3
4
5
6
7
8
9
10
1
2
3
4
R&D
OEM
Industry
Approach Ratings (1=lowest 4=highest)


Integrated DC/DC Converter for Multi-Voltage Bus Systems - Ratings by Number of Responses on Technical Accomplishments
Number or Responses
0
1
2
3
4
5
6
7
8
9
1
2
3
4
R&D
OEM
Industry
Accomplishments Ratings (1=lowest 4=highest)

Industry Comments:
- Not sure what % system cost savings can be achieved
- Good progress on simulation and packaging
- Too focused on steady state response, need assessment of dynamic operating modes
- Well designed project, impressive looking prototype
- Size and cost goals not documented, no cost comparison shown

OEM Comments:
- Not long range R&D, engineering project
- Not 'stretch' enough to justify federal funding

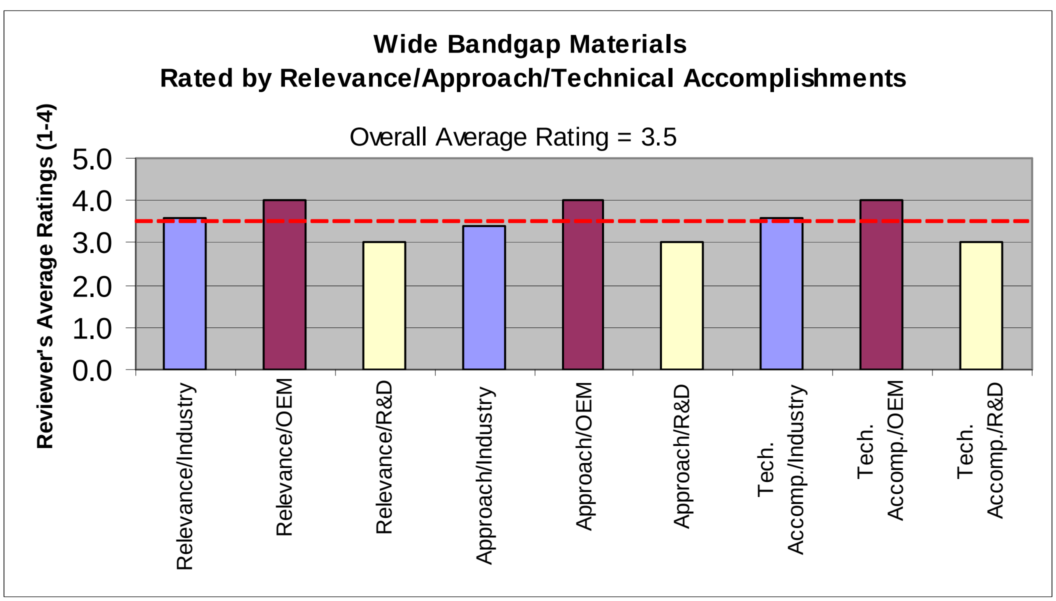
R&D Comments:
- Goals significantly exceed FC goals
- Combining two converters into one with reasonable efficiency and losses is a challenge
- Good simulation, design and development with actual test validation
- Significant progress from previous years effort, efficiency and packaging improved

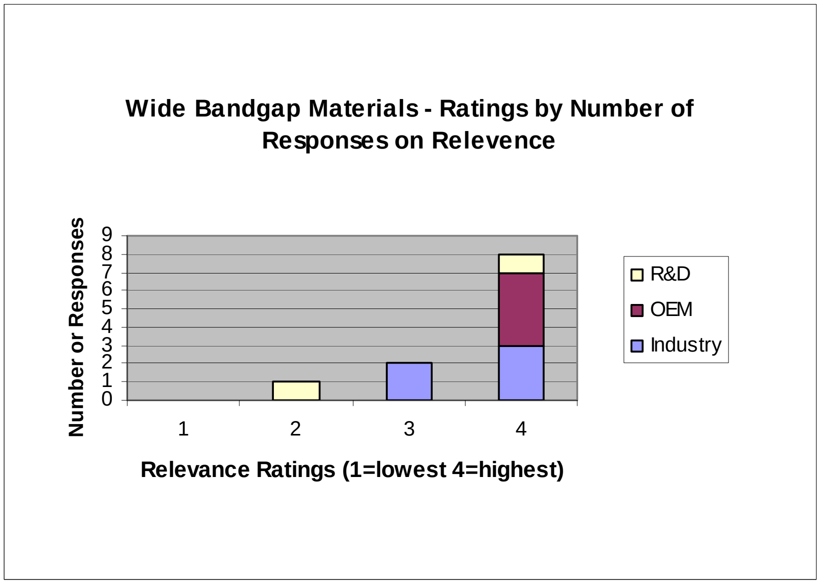
Wide Bandgap Materials
Burak Ozpineci - ORNL

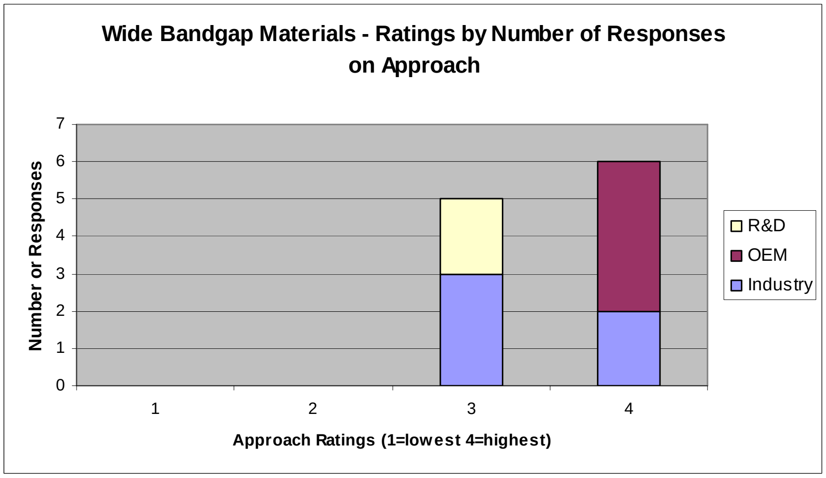
Project Summary: ORNL began evaluating SiC devices in FY01. Since that time this project has evolved to include all wide bandgap devices and this year we evaluated new GaN diodes from Velox. As part of this effort ORNL has established strong relationships with device manufacturers and is able to obtain pre production samples for test.

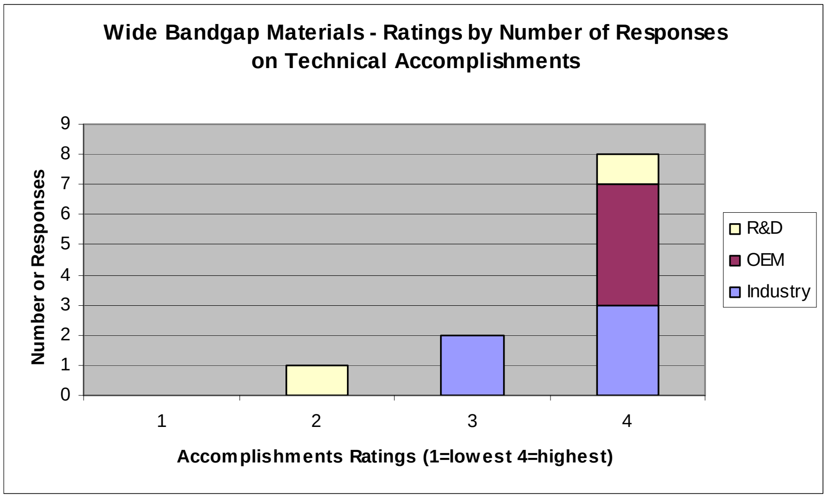
In FY06 this project also included working with the University of Arkansas on high temperature packaging issues with SiC devices as well as modeling of SiC inverters and evaluation of efficiency improvements against a hybrid inverter build in the lab.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.




Wide Bandgap Materials - Ratings by Number of Responses on Relevence
Number or Responses
0
1
2
3
4
5
6
7
8
9
1
2
3
4
Relevance Ratings (1=lowest 4=highest)
R&D
OEM
Industry


Wide Bandgap Materials - Ratings by Number of Responses on Approach
Number or Responses
0
1
2
3
4
5
6
7
1
2
3
4
Approach Ratings (1=lowest 4=highest)
R&D
OEM
Industry


Wide Bandgap Materials - Ratings by Number of Responses on Technical Accomplishments
Number or Responses
0
1
2
3
4
5
6
7
8
9
1
2
3
4
Accomplishments Ratings (1=lowest 4=highest)
R&D
OEM
Industry

Industry Comments:

- Cost and yield are issues
- Would like to see more actual data rather than simulations, how well the devices share current
- Teaming with industry sources and looking at novel combinations of Si and SiC systems seems reasonable approach
- Good team, please to see use of GaN
- Need to hear more about how these high temp components can be integrated into a system
- This is only realistic path to air cooling
- Suggests RFP to work on development of components

OEM Comments:

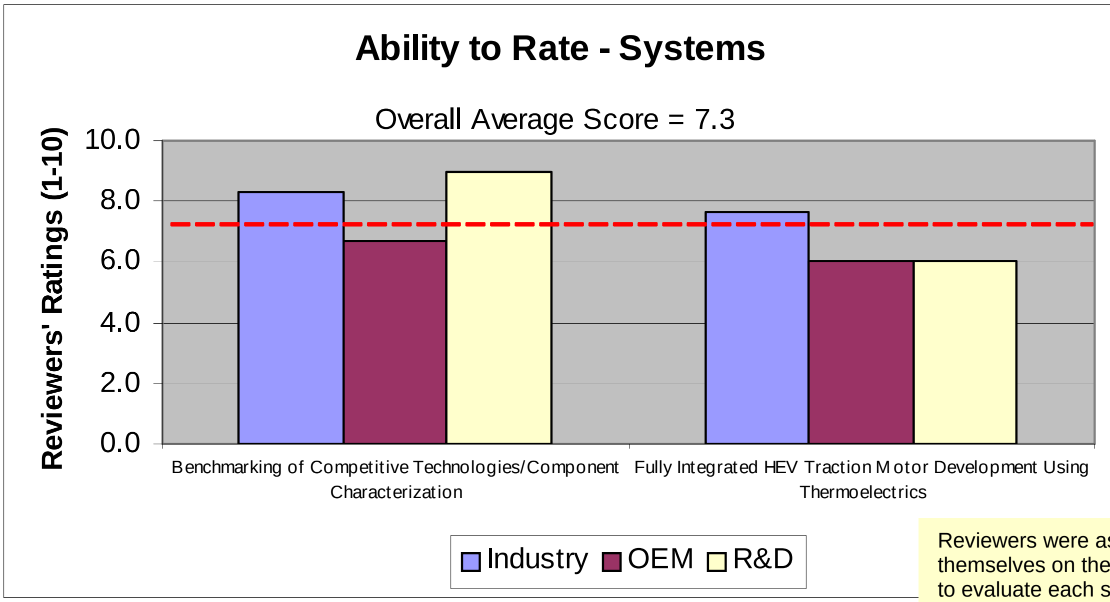
- Good results and progress
- Pleased working on hardware from suppliers rather than spending time/resources on in house design
- One of best projects reported at APEEM review...need to do more
- Good analysis, and report, valuable information, pertinent to the program
- Need to double check accuracy of efficiency data

R&D Comments:

- Definitely high risk, long range program with high payoff
- Goals exceed FC goals, but risk is SiC is unproven technology
- Good approach more fundamental understanding of packaging device interaction is needed
- Excellent simulations, more work needed on packaging and reliability
- SiC should be aimed at higher voltage systems (2 kV) due to high voltage drop, positive temp coefficients
- Numbers appear questionable and controversial, foundation of test results is weak

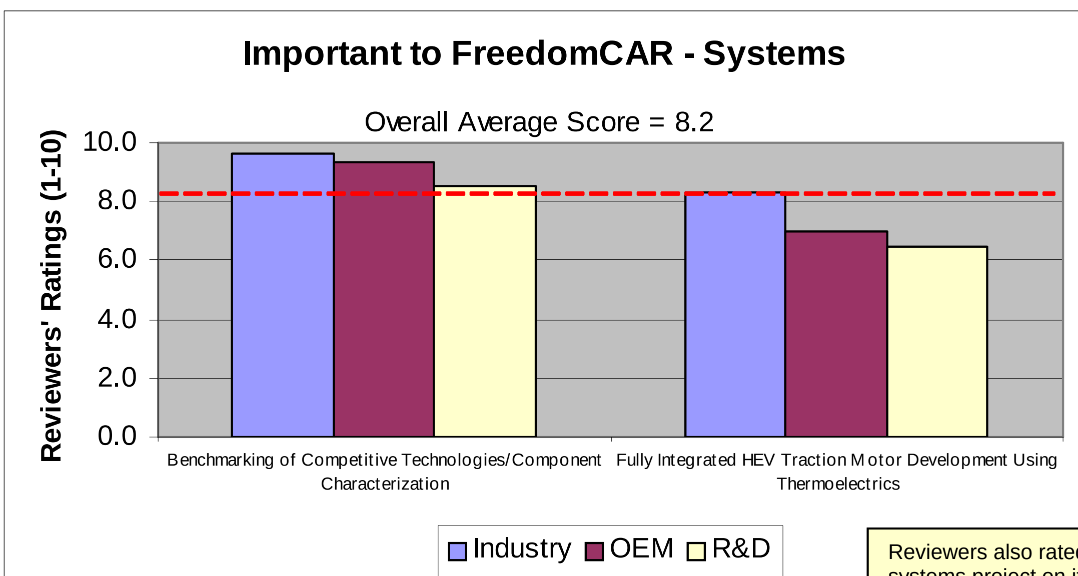
Summary of Project Evaluation Feedback for Systems

The following information provides summaries of the projects that were reviewed and their ratings.



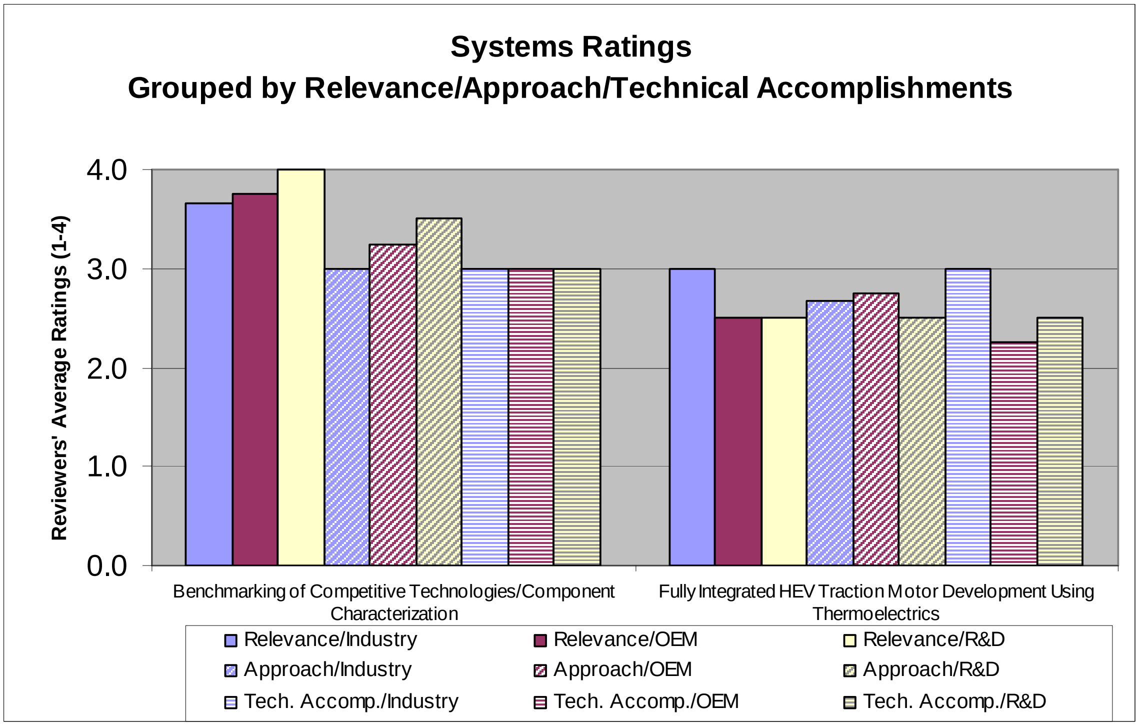
Reviewers were asked to rate themselves on their own ability to evaluate each systems project.

The overall average of all the responses from all reviewers was 7.3/10. Responses ranged from 1 (lowest) to 10 (highest).



Reviewers also rated each systems project on its “importance to meeting FreedomCAR goals.”

The overall average response from all projects and all reviewers was 8.2/10. Responses ranged from 1 (lowest) to 10 (highest).



Reviewers rated each systems project on its "relevance," "approach," and "technical achievement."

Responses ranged from 1 (lowest) to 4 (highest).

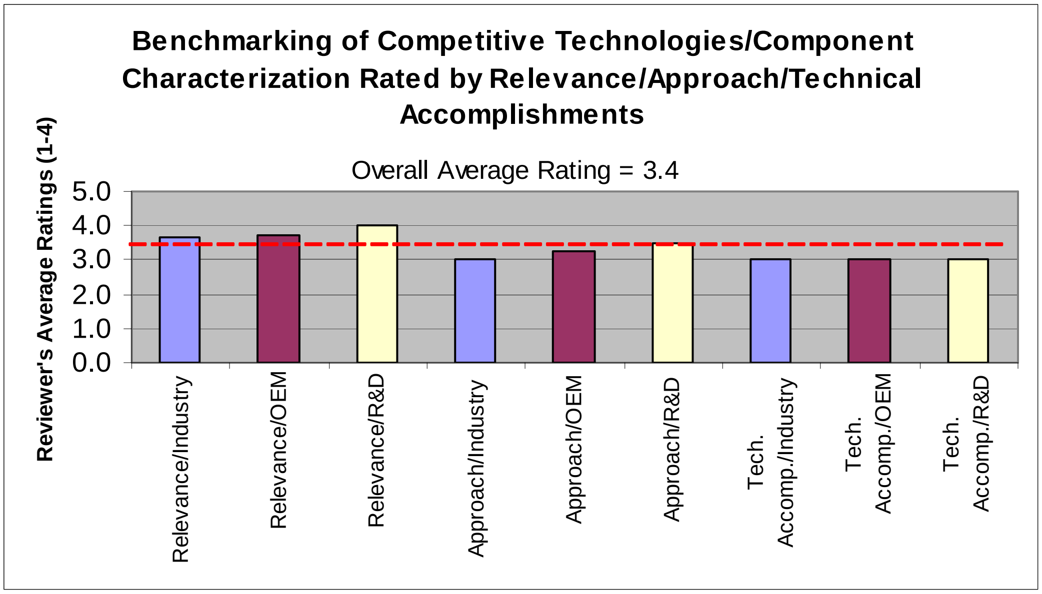
Summary of Project Evaluation Feedback for Specific Systems Projects

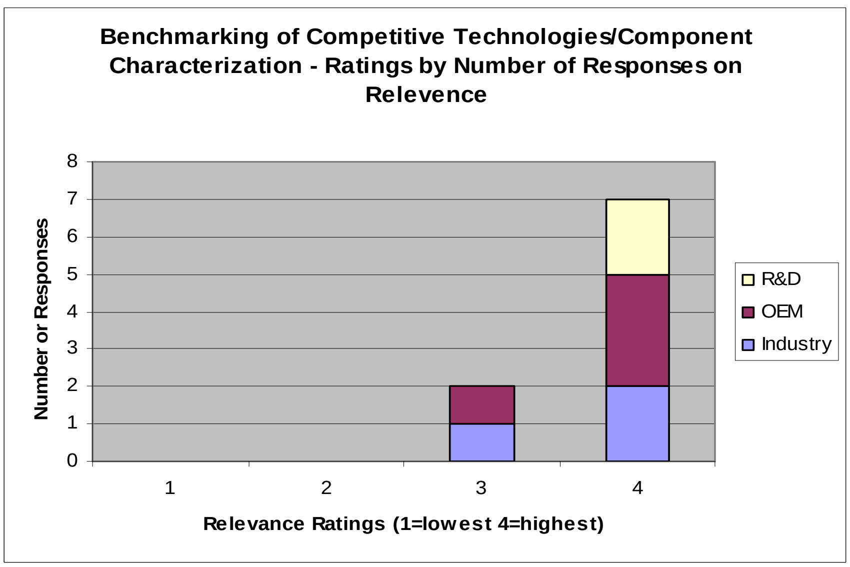
Benchmarking of Competitive Technologies/Component Characterization
Bob Staunton/Larry Seiber - ORNL

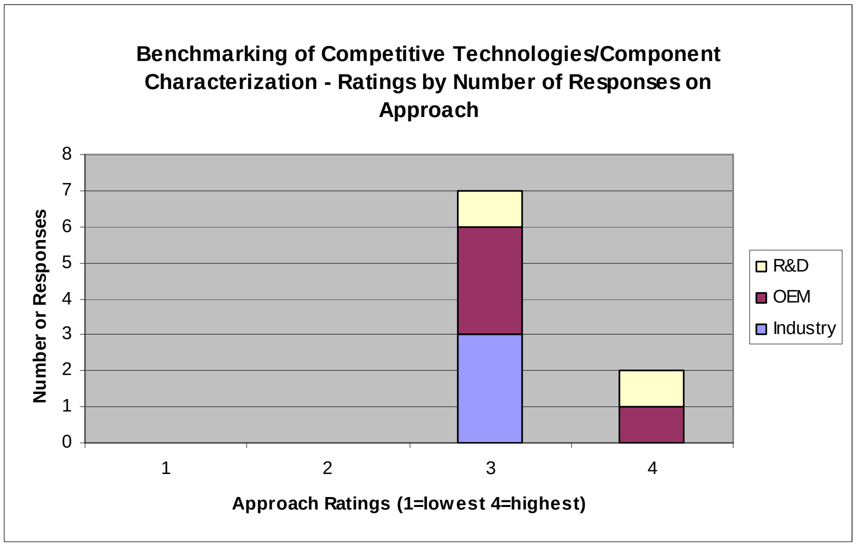
Project Summary: ORNL's benchmarking activities began in FY04 with the Prius motor and inverter assessment. In FY06 the Accord hybrid system was evaluated. Test data, efficiency, design, packaging and fabrication assessments were made to help establish programmatic technical targets.

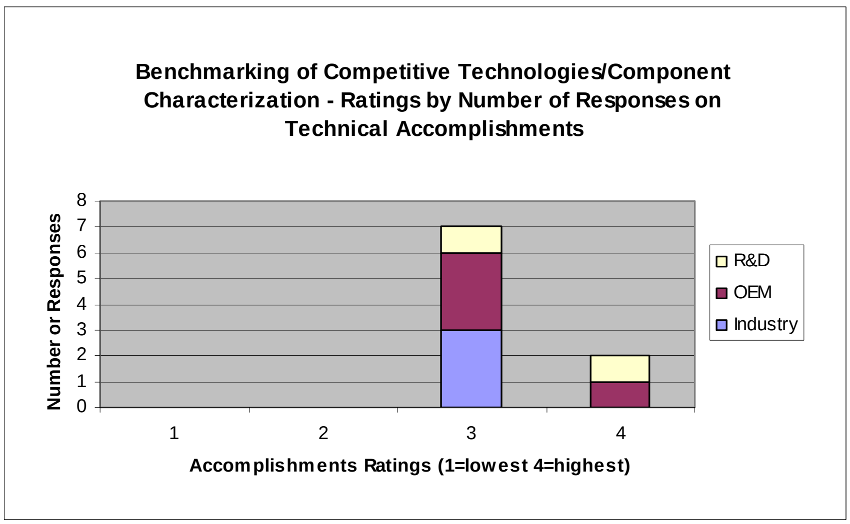
In FY05 the benchmarking effort was expanded to include individual component characterization and analysis to aid in the FCVT capacitor and magnet efforts. Capacitor and magnet test beds were developed along with testing procedures. Commercially available state of the art samples were selected in FY06 and tested to compare to samples from FCVT funded projects.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.


Benchmarking of Competitive Technologies/Component Characterization Rated by Relevance/Approach/Technical Accomplishments
Overall Average Rating = 3.4
Reviewer's Average Ratings (1-4)
5.0
4.0
3.0
2.0
1.0
0.0
Relevance/Industry
Relevance/OEM
Relevance/R&D
Approach/Industry
Approach/OEM
Approach/R&D
Tech. Accomp./Industry
Tech. Accomp./OEM
Tech. Accomp./R&D


Benchmarking of Competitive Technologies/Component Characterization - Ratings by Number of Responses on Relevence
Number or Responses
8
7
6
5
4
3
2
1
0
1
2
3
4
Relevance Ratings (1=lowest 4=highest)
R&D
OEM
Industry





Industry Comments:

- 'It is foundational to document the SOA in helping us not to reinvent the wheel and establish reference points'
- Would like to see more analysis of control schemes by Honda and Toyota
- Test conditions may be problematic, need more detail
- Want to see directional trends
- Supplement work with design analysis

OEM Comments:

- Basic knowledge work that is extremely important, need consistency in benchmarking, critical work
- Need to standardize process and metrics, compare/confirm with vehicle systems work being done at other labs
- Would like to see testing through the full operating range
- More discipline in the gathering and reporting of data

- Consider closer collaboration with ANL...want rigorous procedures that are repeatable and reproducible regardless of the facility

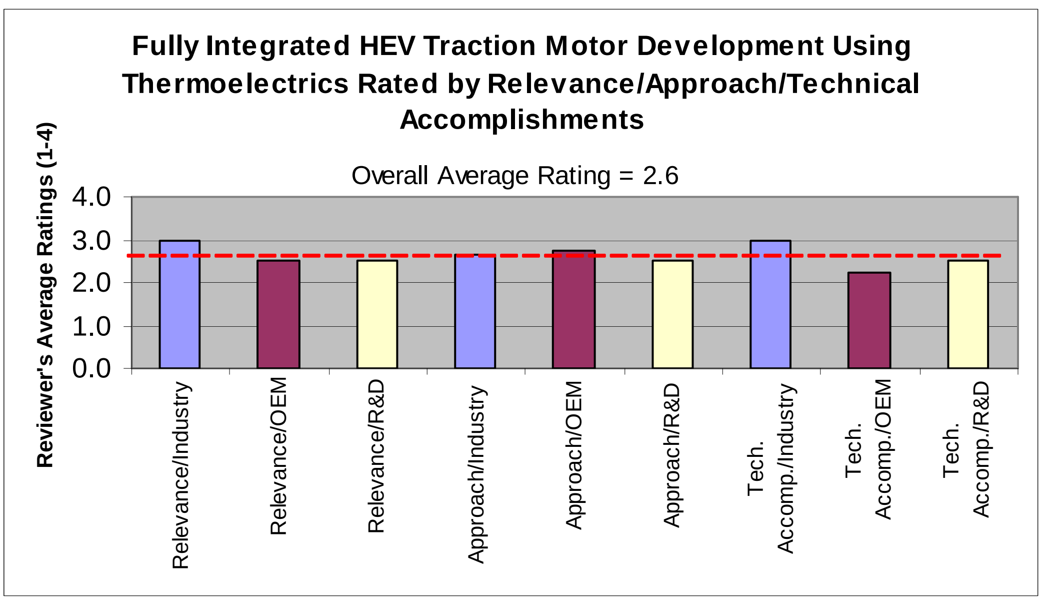
R&D Comments:

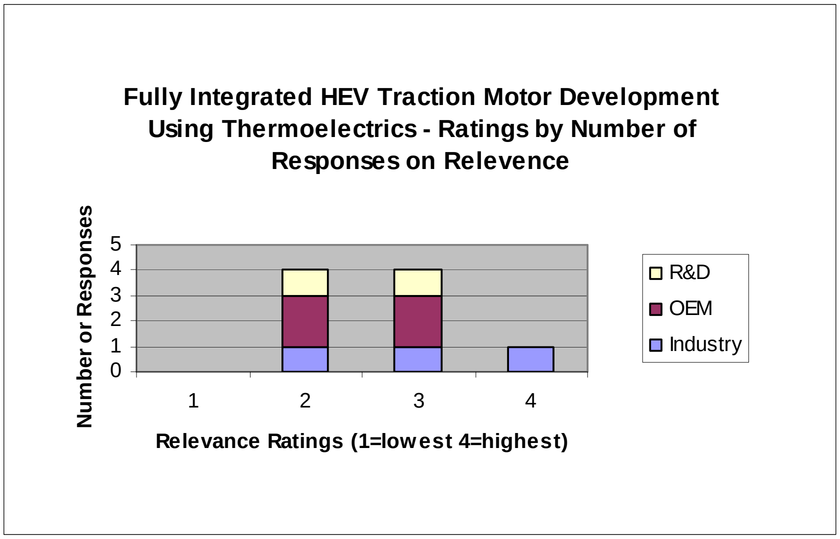
- Good foundation work to help set goals and performance targets
- Need analysis work to support test results
- Good approach to benchmark at all levels, need to track if results are being utilized, integrated into other projects
- Excellent data plotting and characterization of subsystems
- Thought more testing of cap ESL should have been done

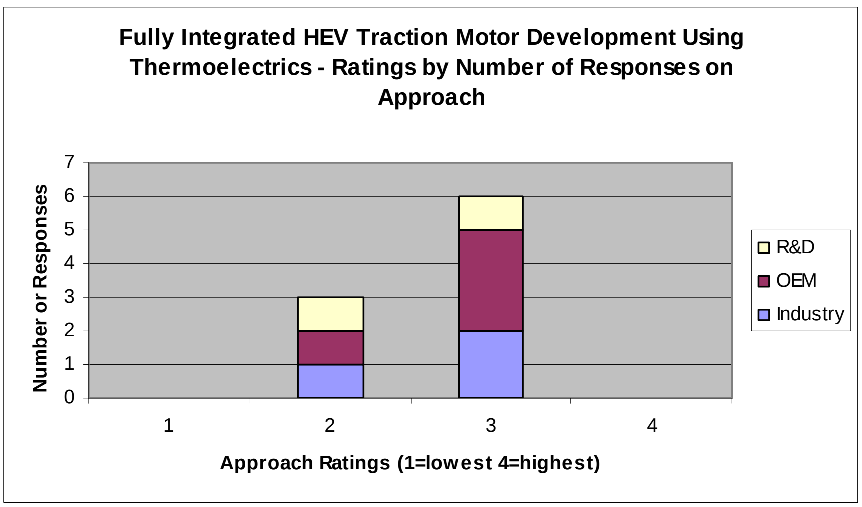
Fully Integrated HEV Traction Motor using Thermoelectrics
Curt Ayers - ORNL

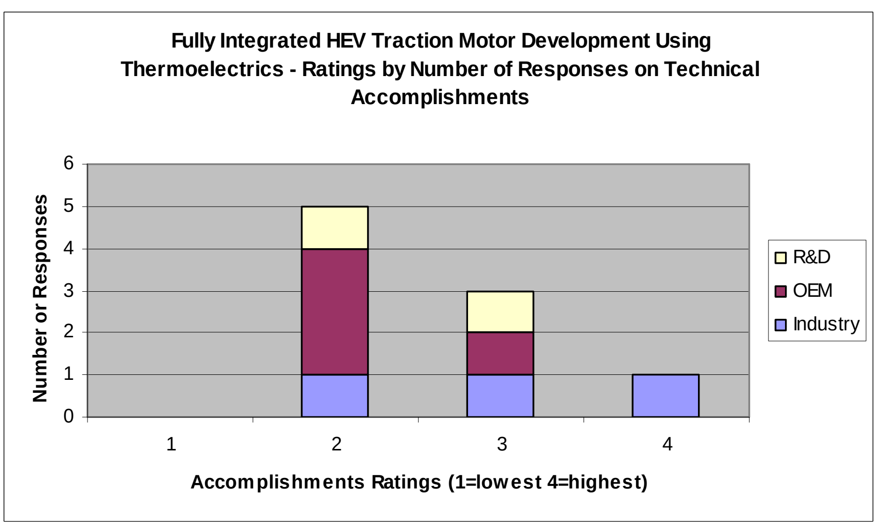
Project Summary: This was a one year effort which evaluated a concept to utilize thermoelectrics in cooling power electronics. The concept enabled silicon components to be used in high temperature environments close to SiC devices. This validation of this technology was essential to the overall end goal of the project which was a novel integrated inverter/motor. In the course of the project it was determined that the thermoelectrics could not perform to the level necessary to achieve the project goals and the effort was 'shelved' until the technology has matured.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.




Fully Integrated HEV Traction Motor Development Using Thermoelectrics - Ratings by Number of Responses on Relevence
Number or Responses
0
1
2
3
4
5
1
2
3
4
Relevance Ratings (1=lowest 4=highest)
R&D
OEM
Industry


Fully Integrated HEV Traction Motor Development Using Thermoelectrics - Ratings by Number of Responses on Approach
Number or Responses
0
1
2
3
4
5
6
7
1
2
3
4
Approach Ratings (1=lowest 4=highest)
R&D
OEM
Industry


Fully Integrated HEV Traction Motor Development Using Thermoelectrics - Ratings by Number of Responses on Technical Accomplishments
Number or Responses
0
1
2
3
4
5
6
1
2
3
4
Accomplishments Ratings (1=lowest 4=highest)
R&D
OEM
Industry

Industry Comments:

- High benefits, if achieved
- ‘Creative’ and compact solution, ‘novel concept’, ‘innovative cooling method’, ‘original’ and very relative to FCVT, ‘excellent’ progress
- Need clearer explanation of what benefits of the approach would be..don’t think the point was well understood by the PI
- One reviewer stated that it seemed the focus is on an area of minor returns for the program

OEM Comments:

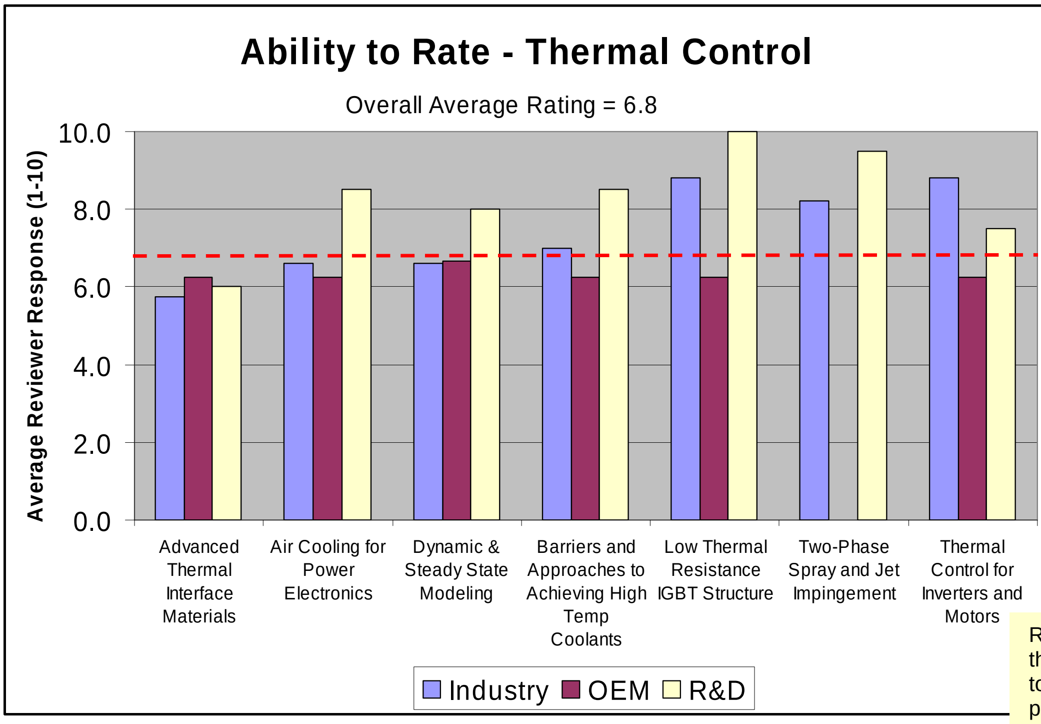
- Nice, quick study, good decision to bookshelf, gaps and cost are too great
- Novel approach, may be ahead of its time
- Agree to delay further work until technology catches up

R&D Comments:

- Thermoelectrics not justified for efficiency and cost
- Inverter does not represent real traction drive inverter
- Need more convincible data to prove the models and application, no realistic system to work with
- Layering approach to TEs shows promise for spot cooling, good design and modeling work
- Agree project should be put on hold until TEs are available

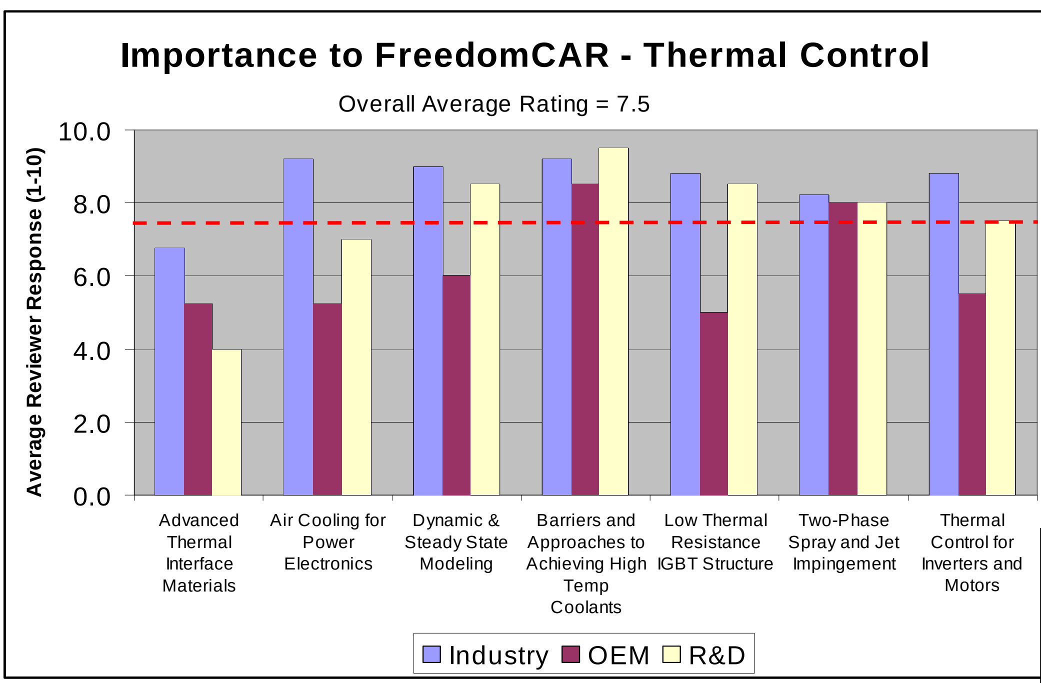
Summary of Project Evaluation Feedback for Thermal Control

The following information provides summaries of the projects that were reviewed and their ratings.



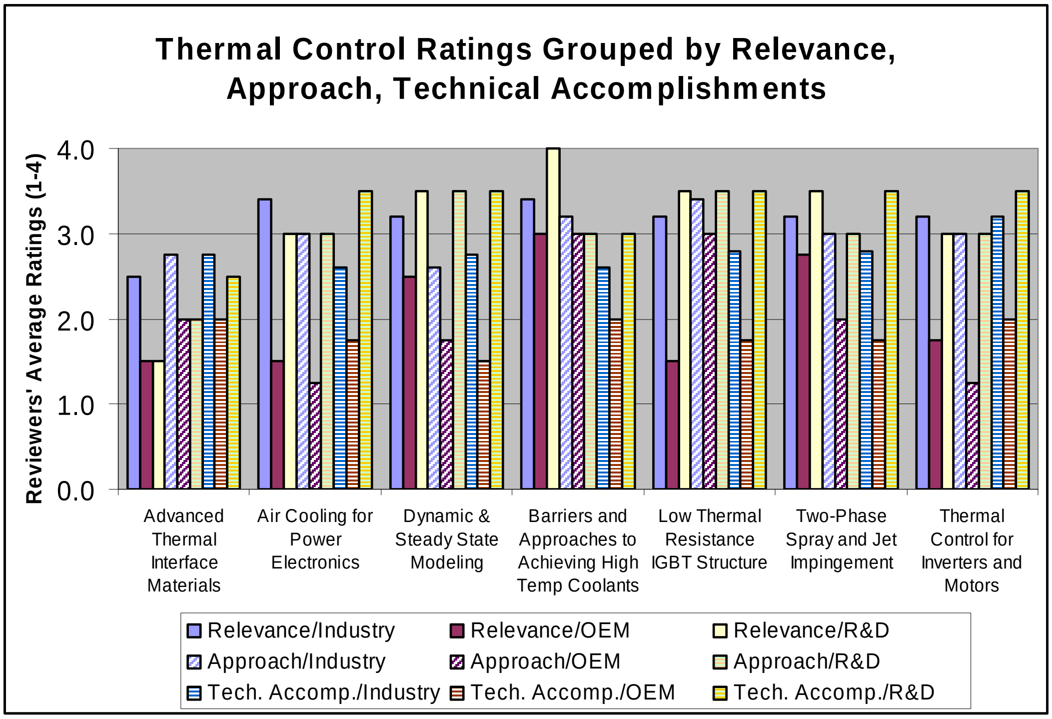
Reviewers were asked to rate themselves on their own ability to evaluate each thermal control project.

The overall average of all the responses from all reviewers was 6.8/10. Responses ranged from 1 (lowest) to 10 (highest).



Reviewers also rated each thermal control project on its "importance to meeting FreedomCAR goals."

The overall average response from all projects and all reviewers was 7.5/10. Responses ranged from 1 (lowest) to 10 (highest).



Reviewers rated each thermal control project on its "relevance," "approach," and "technical achievement."

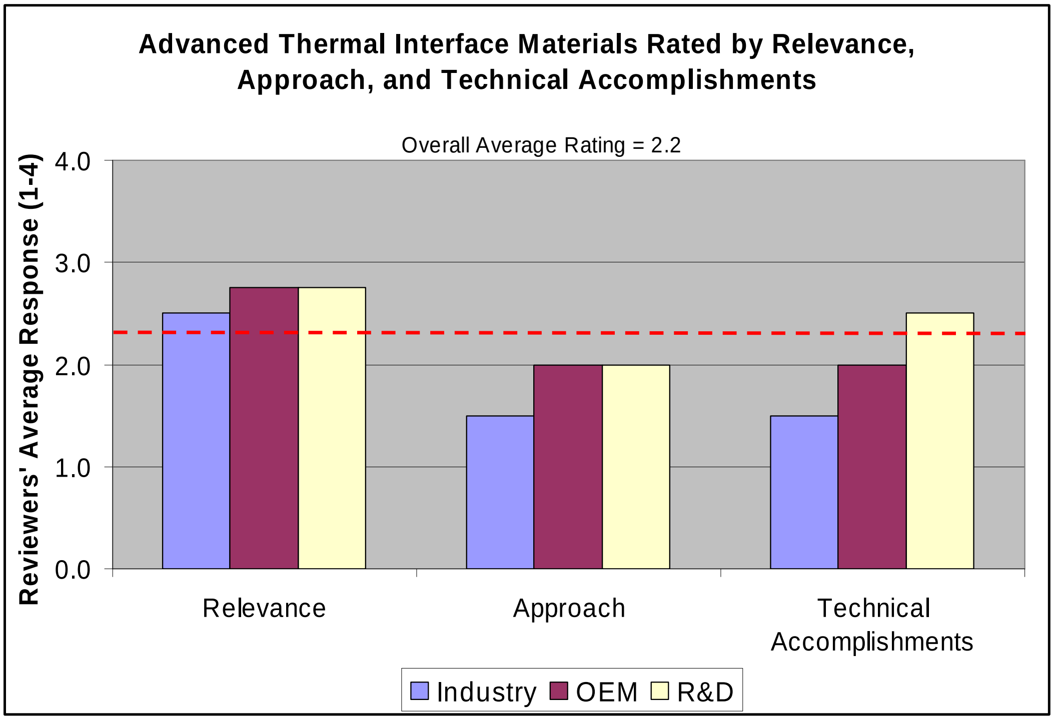
Responses ranged from 1 (lowest) to 4 (highest).

Summary of Project Evaluation Feedback for Specific Thermal Control Projects

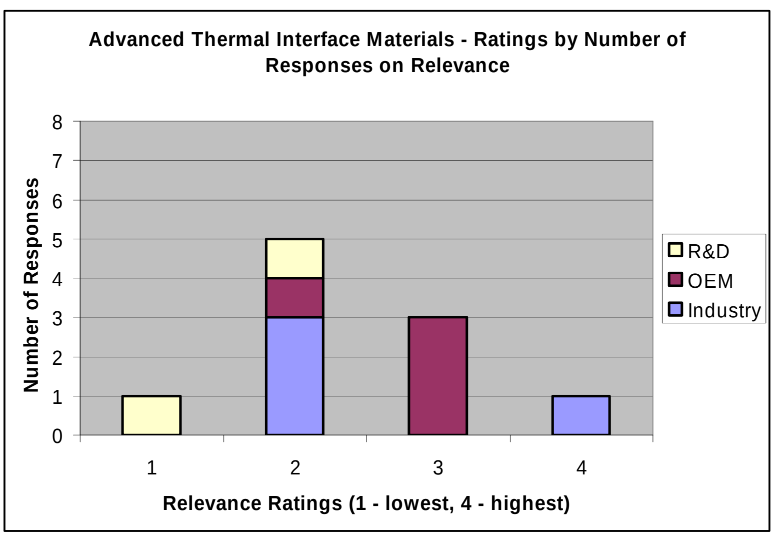
Advanced Thermal Interface Materials to Reduce Thermal Resistance
Sreekant Narumanchi - NREL

Project Summary: FY06 was the first year for this project. The objective of this research is to reduce IGBT package thermal resistance by developing advanced thermal interface materials (TIMs) with increased thermal conductance. Delivery of an advanced TIM is a milestone in the APEEM Roadmap. Specific goals of this project are to identify and assist in the development of low thermal resistance, low cost, thermal interface materials; to characterize thermal performance of novel interface materials over an extended temperature and pressure range, and to characterize the impact of thermal cycling on thermal resistance. Commonly used TIMs such as thermal grease have a thermal conductivity of the order 0.5-1 W/mK. Carbon nanotubes (CNTs) exhibit very high thermal conductivity. Hence CNTs offer an attractive alternative for use in place of conventional TIMs. In FY07, we will broaden the focus of this project to evaluate and develop other alternative approaches such as metal coated particles, and will provide both performance and cost assessments.

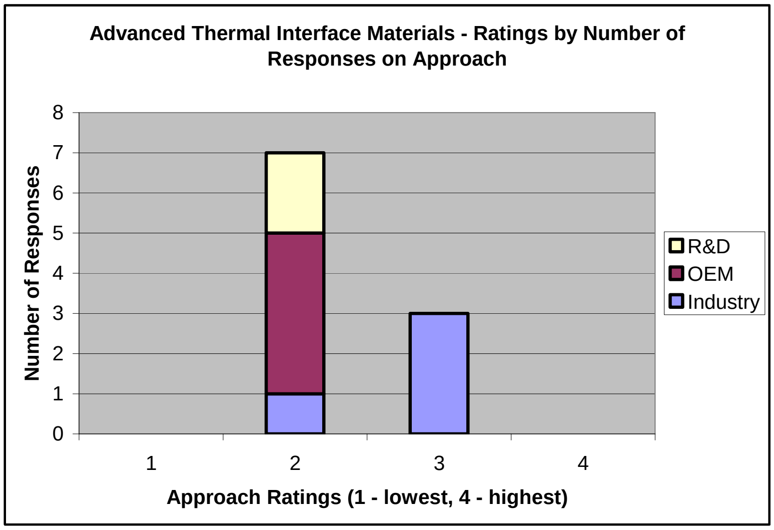
Charts summarizing reviewers' ratings and reviewers' comments are shown below.

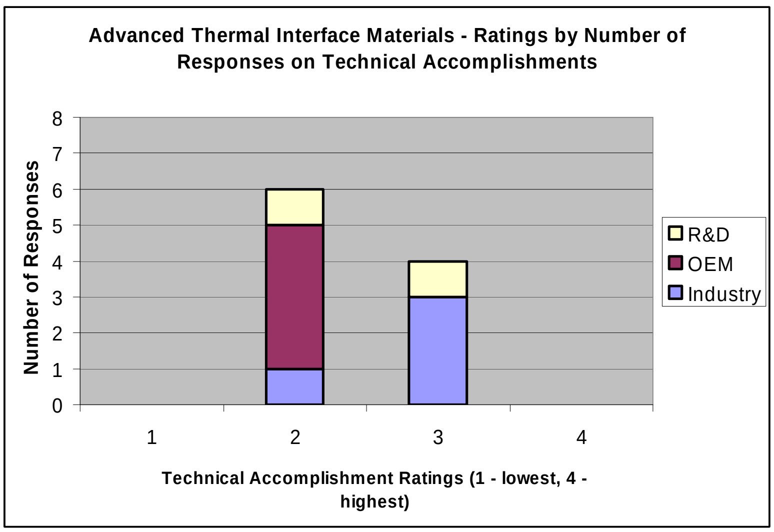


Advanced Thermal Interface Materials Rated by Relevance, Approach, and Technical Accomplishments
Overall Average Rating = 2.2
Reviewers' Average Response (1-4)
4.0
3.0
2.0
1.0
0.0
Relevance
Approach
Technical Accomplishments
Industry
OEM
R&D



Advanced Thermal Interface Materials - Ratings by Number of Responses on Relevance
Number of Responses
8
7
6
5
4
3
2
1
0
1
2
3
4
Relevance Ratings (1 - lowest, 4 - highest)
R&D
OEM
Industry





Industry Comments:

- Improving thermal interface materials is important
- There are a number of superior alternatives to CNTs; eliminate the barrier, direct die-bonding
- Need to get more thermal improvement
- Good fundamental S&T, progress looks exciting
- CNT's too costly, need a transition/commercialization strategy
- Need to evaluate degradation, thermal cycling

OEM Comments:

- CNT's too costly and too complex
- Other mechanical methods may be superior
- Innovative application of CNT's, but limited practicality
- May not substantially contribute to meeting FreedomCAR goals

R&D Comments:

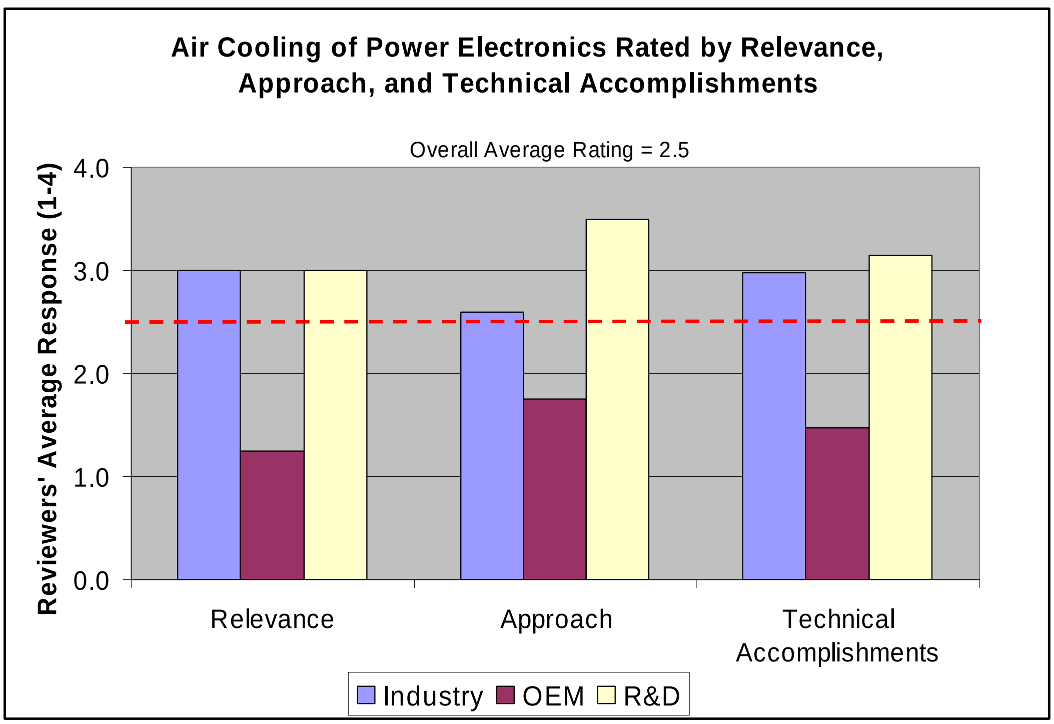
- CNT's are too far out with too many uncertainties

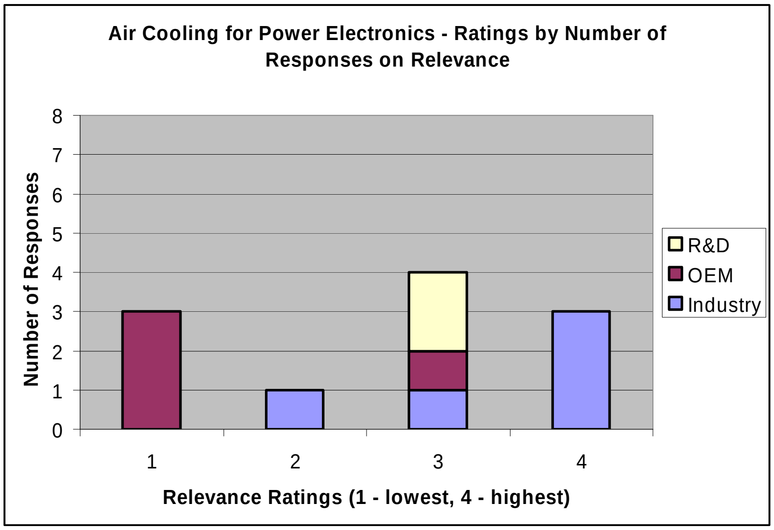
- Other technologies (composite materials and/or alloys) hold more promise
- Shift focus away from CNT's
- Thermal interface materials are an important concern and should be studied
- CNT's not likely to be cost effective and reliable

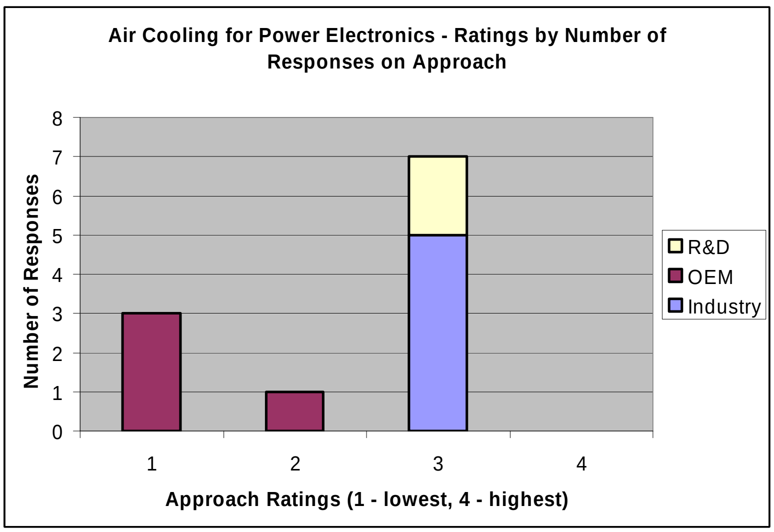
Air Cooling for Power Electronics
Desikan Bharathan - NREL

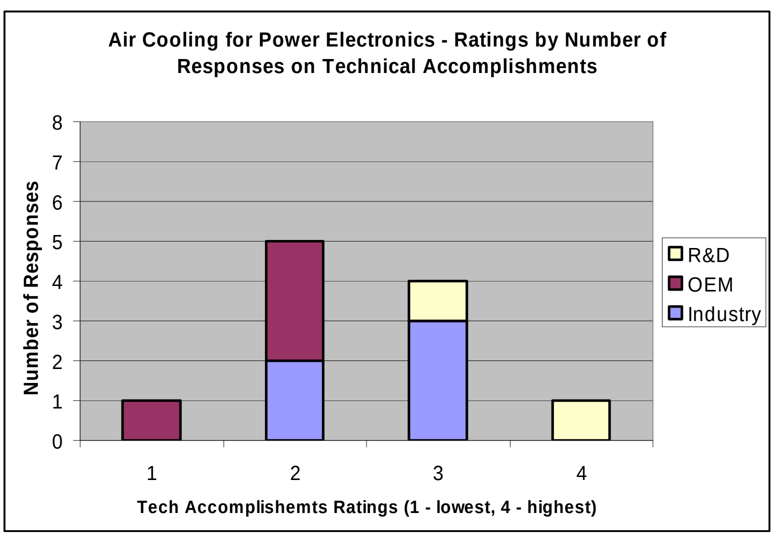
Project Summary: FY06 was the first year for this project. The objective is to assess the potential for reducing the cost and complexity of the cooling system for power electronics using air. This research will result in quantifying the relative merits for the use of air for cooling power electronic devices to achieve high heat flux removal rates under steady state and transient conditions. Specific goals for FY06 included: investigation of practical hardware commonly used in mission-critical applications (such as turbine blade cooling); identify hardware available in the industry; conduct systems level analyses to assess performance and parasitic power; conduct CFD investigations to assess heat transfer potential. The goal initial goal of this research is to characterize and assess the performance limits, design approaches, and system considerations of air cooling. The application to SiC technology will continue to be a priority and we will express the thermal performance results in terms of SiC. Experimental validation and system integration issues will be key areas of focus for this project in FY07.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.




Air Cooling for Power Electronics - Ratings by Number of Responses on Relevance
Number of Responses
0
1
2
3
4
5
6
7
8
1
2
3
4
Relevance Ratings (1 - lowest, 4 - highest)
R&D
OEM
Industry


Air Cooling for Power Electronics - Ratings by Number of Responses on Approach
Number of Responses
0
1
2
3
4
5
6
7
8
1
2
3
4
Approach Ratings (1 - lowest, 4 - highest)
R&D
OEM
Industry


Air Cooling for Power Electronics - Ratings by Number of Responses on Technical Accomplishments
Number of Responses
0
1
2
3
4
5
6
7
8
1
2
3
4
Tech Accomplishemts Ratings (1 - lowest, 4 - highest)
R&D
OEM
Industry

Industry Comments:

- This is the ultimate solution for cooling the power electronics and motor
- Good start on modeling, but measured data is needed
- Need to validate the assumed heat transfer coefficients used
- Appears to be relatively early in the project stage. Lots of literature research and commercial analysis is complete.
- Air cooling high temp power electronics is perhaps the most disruptive breakthrough for the FreedomCAR Program
- The results to date are interesting, encouraging, but no breakthrough
- Liquid (or two phase) cooling of electronics is likely to prevail
- Improvements are still fairly nominal. No breakthroughs were achieved
- Very high velocities, potentially creating audible noise, along with material erosion are problems not addressed
- Identified aggressive goals

OEM Comments:

- This project must be worked on in the context of silicon carbide
- Total systems implications need to be identified and quantified
- Air cooling is unlikely to be practical
- PI should evaluate air cooling when ambient air temperatures are over 100-120°F
- PI suggests that this approach may be beneficial when SiC technologies become available, but if SiC meets its expectation, the temperature characteristics would not require sophisticated air cooling

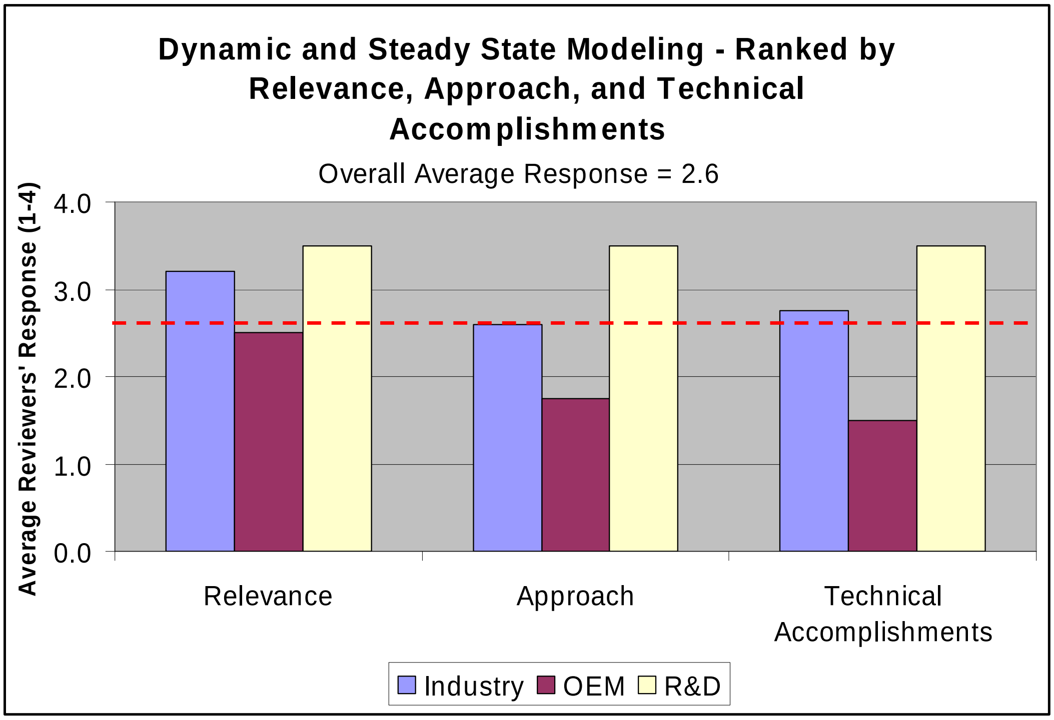
R&D Comments:

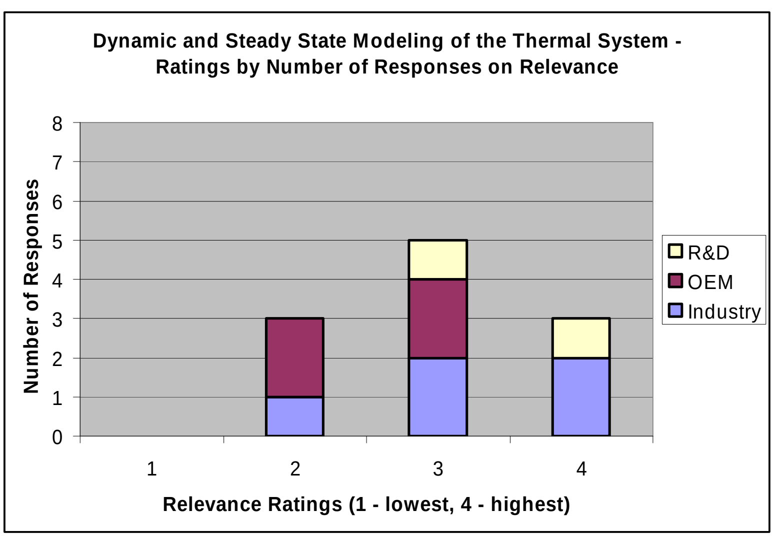
- Need experimental results, including acoustics
- Overall, the approach is good and appropriate, the most innovative technologies have been identified, but system level issues need to be addressed
- Identified & simulated very high performance air cooling system
- Air cooling is a low cost, preferred method for cooling consumer and automotive electronics
- Microjet coolers have potential for significant increased air cooling performance.
- Good progress of CFD analysis of airflow in the microjet devices and on analysis of improved cooling
- Microjet coolers promise low cost, high reliability cooling improvement
- Need to focus on system integration issues

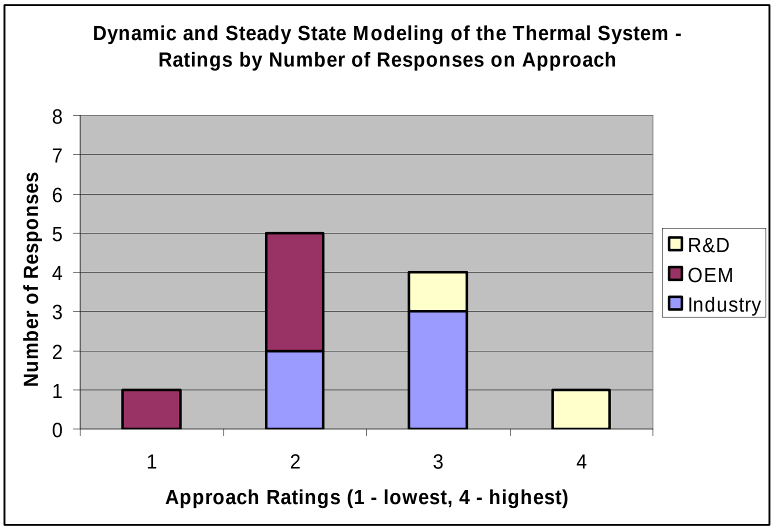
Dynamic and Steady State Modeling to Identify, Over Various Drive Cycles, Component and System Performance Efficiency and Thermal Loads
Michael O'Keefe - NREL

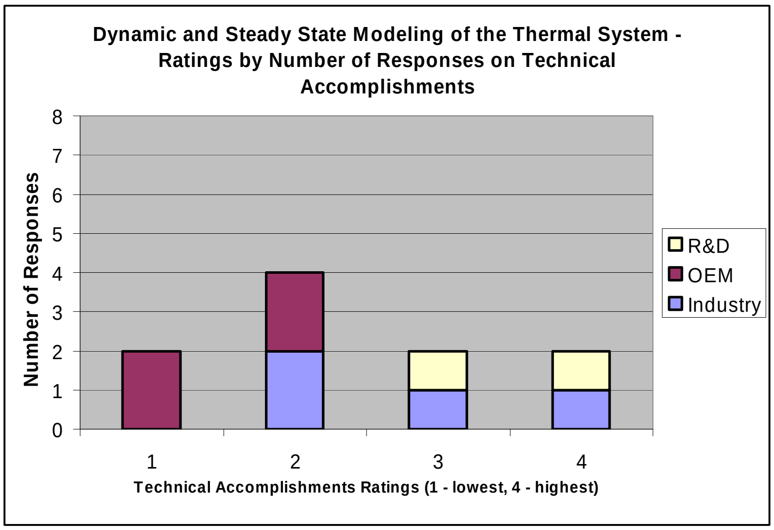
Project Summary: FY06 was the first year for this project. The objective of this proposal is to simulate dynamic drive-cycle events in electric drivelines to comprehensively determine components' influence and impact on thermal design and operation under real-conditions. The focus of this project is to identify critical thermal control needs to enable commercially viable advanced automotive systems (HEV, PHEV, FCV), to identify and assess in a systems context the most appropriate thermal control technologies that meet those needs, and to recommend a thermal control R&D pathway. In FY06 this project focused on developing an understanding of how vehicle duty cycle influences the thermal loading of PEEM components for various powertrains (PHEV, HEV, etc.), and developing models to conduct an evaluation of thermal control technologies in the context of a steady-state model of an IGBT assembly in an inverter. In FY07, this project will focus on a consistent methodology for evaluating the various thermal control technologies under development from a thermal subsystem perspective and developing the tools necessary to assess the effect and the tradeoffs of improved thermal performance and system reliability and life.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.









Industry Comments

- This system's engineering level project is necessary and adds rationale to APEEM focused projects in machines, power electronics, and thermal controls
- Must add in clarification of vehicle propulsion system top level control approach
- Need to improve project focus and roadmap on how it all ties together
- Good comparison of HEV and PHEV PEEM efficiency
- Risk is that conclusions could be compromised by conventional wisdom
- Data interesting and revealing, but need to develop validation data
- Does not appear to be tied to goals
- Adapt an existing model

OEM Comments

- Needs motor and motor inverter duty cycle and heat generation and temperature impact on the components
- Focus on sub-systems! Need to get to the impacts on the components (inverters and motors, for example)
- Assess all implications (wt, vol.) for each alternative technology approach

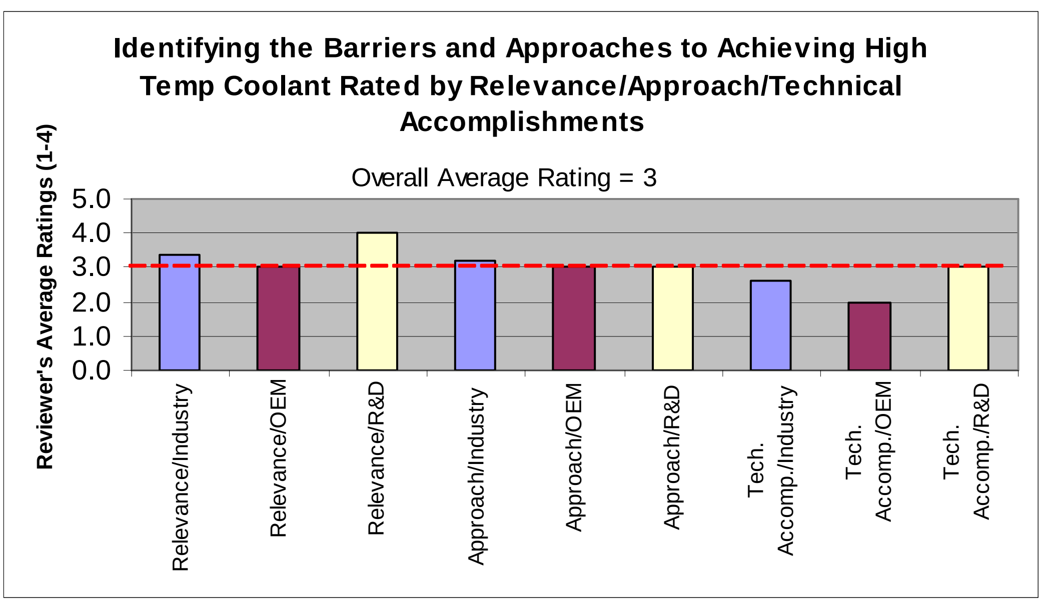
- Don't dwell on vehicle architectures
- The assignment of a continuous rating to components (such as inverters and motors) needs to have the benefit of this sort of work looking at duty cycles
- Great to be looking at the whole system
- Project has great potential if it focuses on components
- Diversion to vehicle level modeling and distraction into PHEV work seem irrelevant to the task described in Project objectives
- PI and lab have excellent modeling and thermal management capabilities

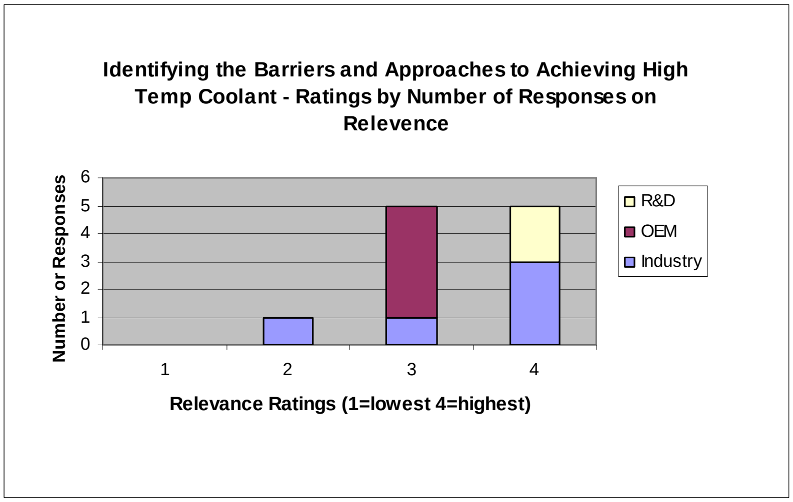
R&D Comments
- The goals of this work are fundamental to the FreedomCAR Program
- Researchers have taken appropriate approaches from the global to micro approach.
- System level models incorporating specific thermal control models is real useful and important
- This provides the focus necessary to ensure that the needs are being met cost effectively
- The focus of flowing duty cycle to thermal requirements is a very effective technical approach to addressing what are the power and thermal requirements for FreedomCAR.
- Excellent differentiation of CV, HEV, PHEV, and FCV
- Conversion of duty cycle to thermal & power requirements needs to define approach for assessing thermal projects against FreedomCAR needs

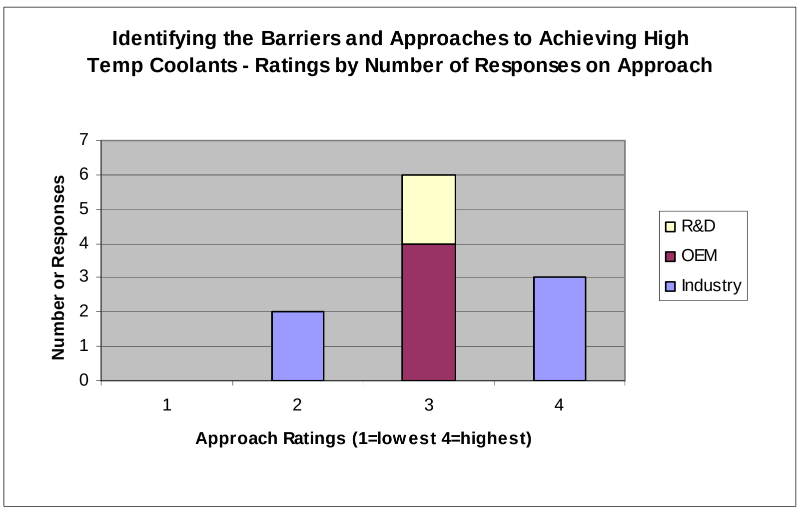
Identifying the Barriers and Approaches to Achieving High Temp Coolants
Bob Staunton-ORNL

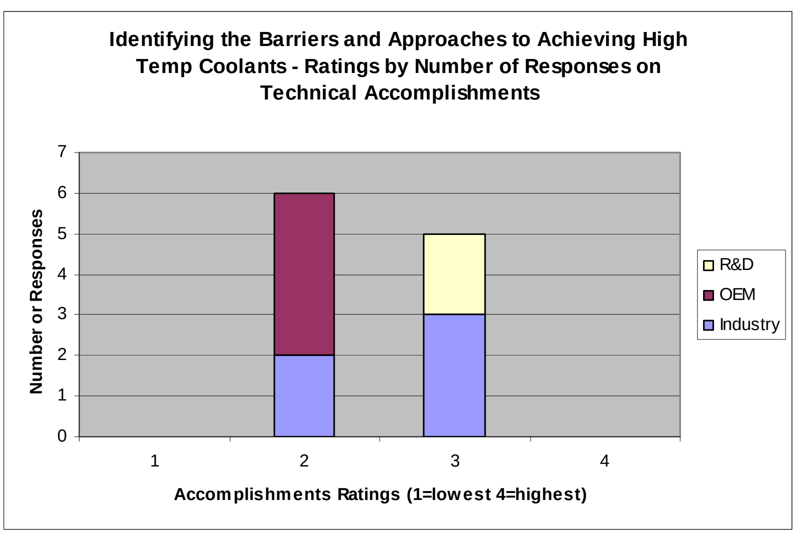
Project Summary: This project was a small effort which came about as a request from the OEMs to evaluate what barriers existed to utilizing the 105°C engine coolant for cooling power electronics. It was a one year study to assess the significant areas which might be problematic and to determine cost benefits/penalties in moving from a dedicated cooling loop to the use of the existing coolant loop.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.




Identifying the Barriers and Approaches to Achieving High Temp Coolant - Ratings by Number of Responses on Relevence
Number or Responses
0
1
2
3
4
5
6
1
2
3
4
Relevance Ratings (1=lowest 4=highest)
R&D
OEM
Industry


Identifying the Barriers and Approaches to Achieving High Temp Coolants - Ratings by Number of Responses on Approach
Number or Responses
0
1
2
3
4
5
6
7
1
2
3
4
Approach Ratings (1=lowest 4=highest)
R&D
OEM
Industry


Identifying the Barriers and Approaches to Achieving High Temp Coolants - Ratings by Number of Responses on Technical Accomplishments
Number or Responses
0
1
2
3
4
5
6
7
1
2
3
4
Accomplishments Ratings (1=lowest 4=highest)
R&D
OEM
Industry

Industry Comments:
- Points out issues but offers no solutions
- Simplistic approach
- Should have had more info on reliability issues
- Lack of engineering rigor
- Not a development task
- Good systematic approach

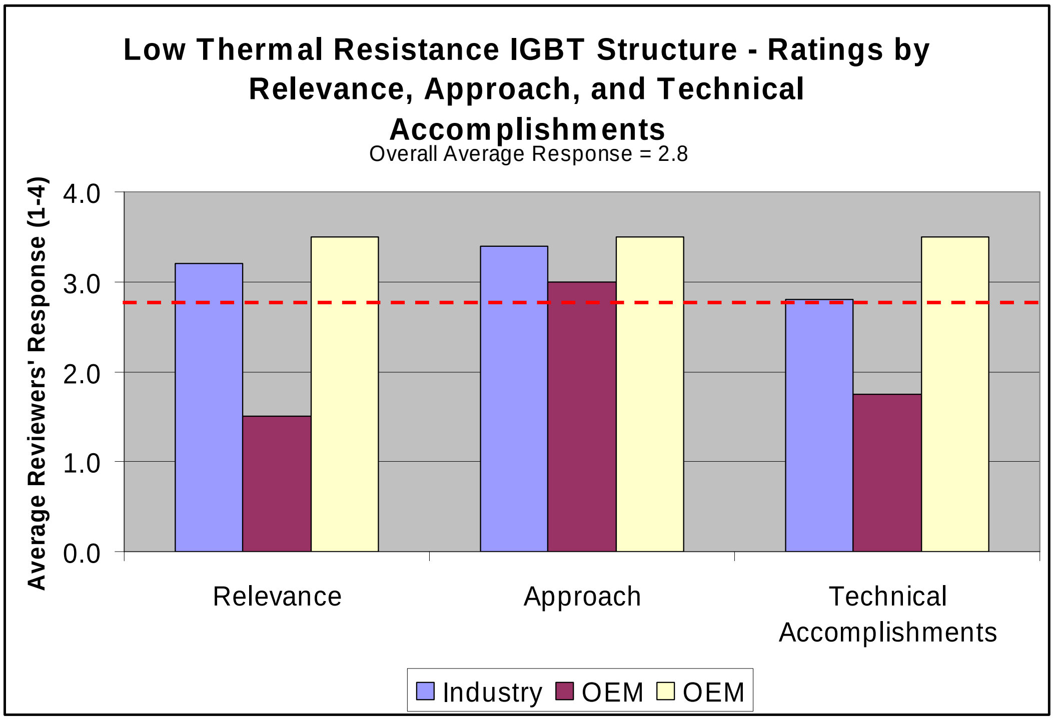
OEM Comments:
- Needs more detailed work
- Need to get specialists involved
- Expected more progress
- Not innovative, but nonetheless necessary work

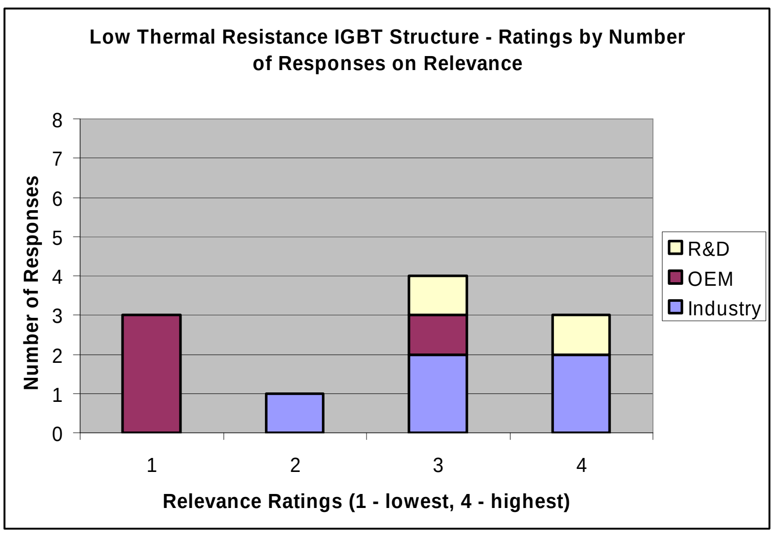
R&D Comments:
- Good work, good suggestions for improvement,
- Simplistic analysis, needs more depth
- Work shows significant data collection and analysis
- Doesn't account for packaging..significant cost factor
- Need to address more technical issues before cost analysis can be made

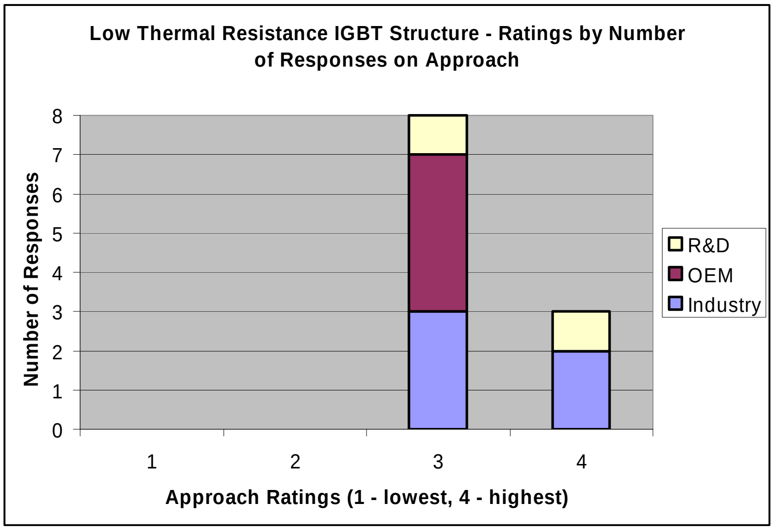
Low Thermal Resistance IGBT Structure
Keith Gawlik - NREL

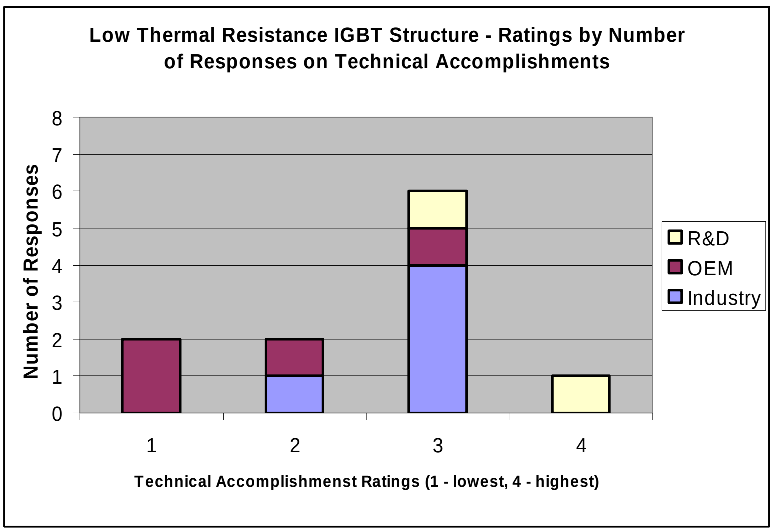
Project Summary: FY06 was the second year for this project. The objective of this project is to reduce the thermal resistance between the silicon die of the IGBT and the coolant. By reducing the thermal resistance, a target coolant temperature of 105°C can be used to cool the inverter electronics. This project was initiated as a modeling study of the potential impact of eliminating several of the thermal layers within the IGBT structure. Finite element models and computational fluid dynamics models showed that it may be possible to maintain 125°C maximum junction temperatures using 105°C coolant. This project uses fundamental results from the jet and spray cooling modeling project, but also requires the development and demonstration of system integration issues. In FY06 a CRADA was established with an industry partner to develop a working prototype to validate the modeling results and to explore issues such as reliability and erosion. The prototype of the heat exchanger was built near the end of FY06. In FY07, the plan is to test the heat exchanger performance using an industry supplied inverter, to optimize the design, evaluate key operational parameters such as reliability, and finally transfer the technology to industry. The technology is adaptable to other inverter designs, and the project will be completed upon transfer to industry late in FY07 or early FY08 – depending on the results from the initial prototype.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.


Low Thermal Resistance IGBT Structure - Ratings by Relevance, Approach, and Technical Accomplishments
Overall Average Response = 2.8
Average Reviewers' Response (1-4)
4.0
3.0
2.0
1.0
0.0
Relevance
Approach
Technical Accomplishments
Industry
OEM
OEM


Low Thermal Resistance IGBT Structure - Ratings by Number of Responses on Relevance
Number of Responses
8
7
6
5
4
3
2
1
0
1
2
3
4
Relevance Ratings (1 - lowest, 4 - highest)
R&D
OEM
Industry





Industry Comments

- The approach is well thought out but needs measured data
- Good near-term benefit project to use 105°C coolant. Gives "reality-check". Feedback useful for longer-term developments.
- Need to address long-term performance issues such as sealing, degradation of fluid, contamination, and pressure drop, vibration effects, erosion, transient power effects, and pump requirements
- Used results from jet testing on small scale to develop a detailed design for complete inverter cooling
- The project has the potential of delivering a technical breakthrough
- Technical approach appears to be well formulated to deal with the many challenges through combination of analytical design and empirical efforts
- Excellent progress on analytical design. Good progress on fabricating prototype.
- Jet cooling appears to have sufficient opportunity to gain power density
- Teaming with industry in doing both modeling and experimentation is reasonable

OEM Comments

- Not a long-range and high-risk R&D
- Need comprehensive assessment of system implications including cost
- Great effort to demonstrate technology

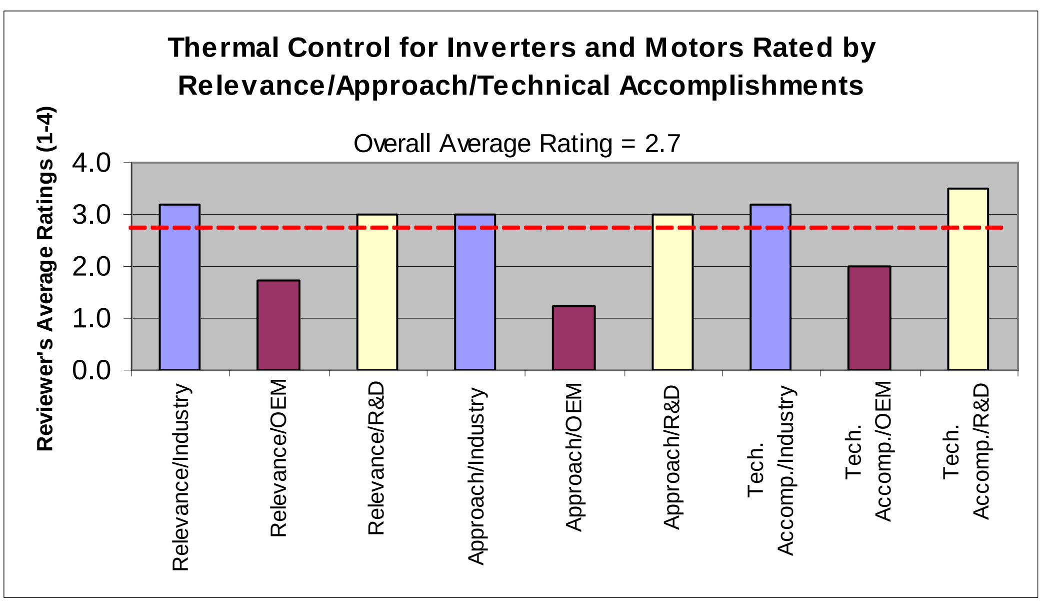
R&D Comments

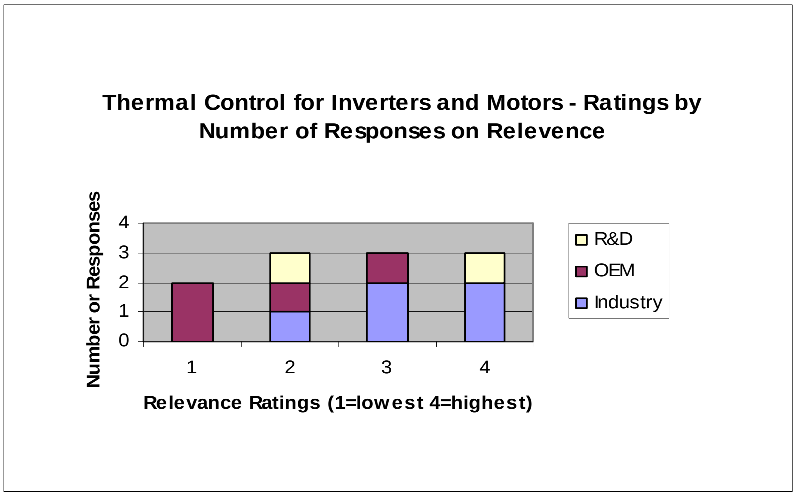
- Need to address reliability when impinging high pressure liquid on the bottom of DBC
- Still need extensive reliability work to assess stress on die, stress on interconnect, and erosion of DBC surface
- Thermal modeling showing excellent heat flux cooling moving toward prototype
- Need modeling/experiments addressing interconnect reliability, cracking, and DBC erosion as a result of direct liquid Impingement
- This work is fundamental to achieving the power density goals of the FreedomCAR program
- I believe the logical, careful approach used here is very sound
- The amount of work completed seems quite good
- Tight collaboration with industry partner
- Looking forward to the report - really looking forward to data!

Thermal Control for Inverters and Motors
John Hsu/Curt Ayers - ORNL

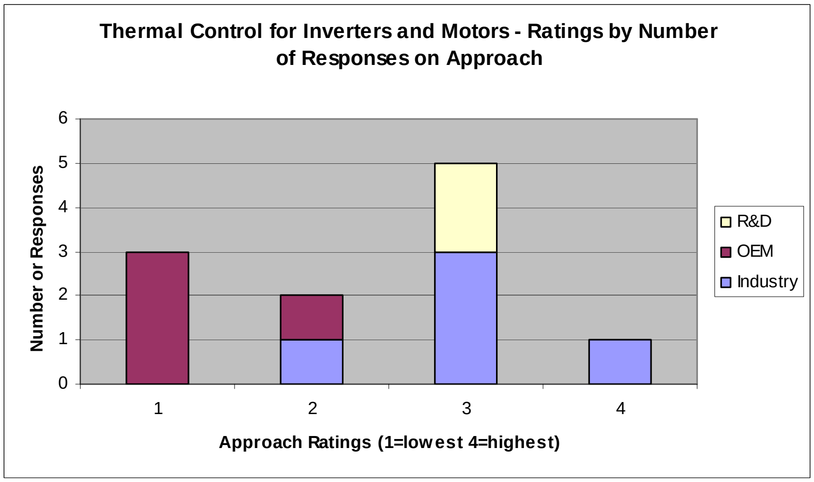
Project Summary: The floating loop and reduced size inverter project began in FY04. The floating loop test bed is complete and functioning as a stand alone vehicle air conditioning system. The reduced size inverter (1/2 the size of the Semikron inverter) has been built this year and is under test. The inverter incorporates new capacitor technologies as well as new low temperature sintered direct die attachments. Extensive evaluations of component effects in R134a have been undertaken as well as detailed dielectric studies of various coolants as part of the preliminary work on this project.

Charts summarizing reviewers' ratings and reviewers' comments are shown below.

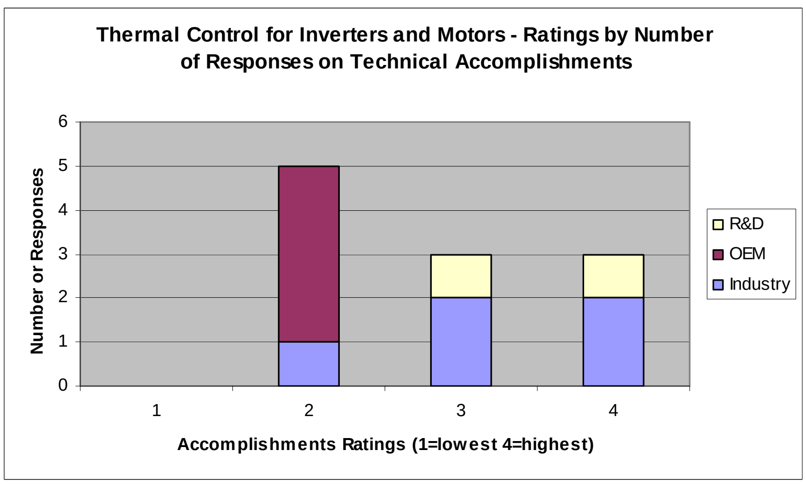




Thermal Control for Inverters and Motors - Ratings by Number of Responses on Relevence
Number or Responses
Relevance Ratings (1=lowest 4=highest)
R&D
OEM
Industry



Thermal Control for Inverters and Motors - Ratings by Number of Responses on Approach
Number or Responses
Approach Ratings (1=lowest 4=highest)
R&D
OEM
Industry



Thermal Control for Inverters and Motors - Ratings by Number of Responses on Technical Accomplishments
Number or Responses
Accomplishments Ratings (1=lowest 4=highest)
R&D
OEM
Industry

Industry Comments:
- Interesting approach, a lot of technical challenges
- Questions concerning how approach effects the size of the condenser
- ‘Novel approach’, worthy of pursuing, ‘out of the box thinking’
- Can achieve major advances in packaging and performance
- Question if could take voltage higher in R134a for added benefits in the electronics

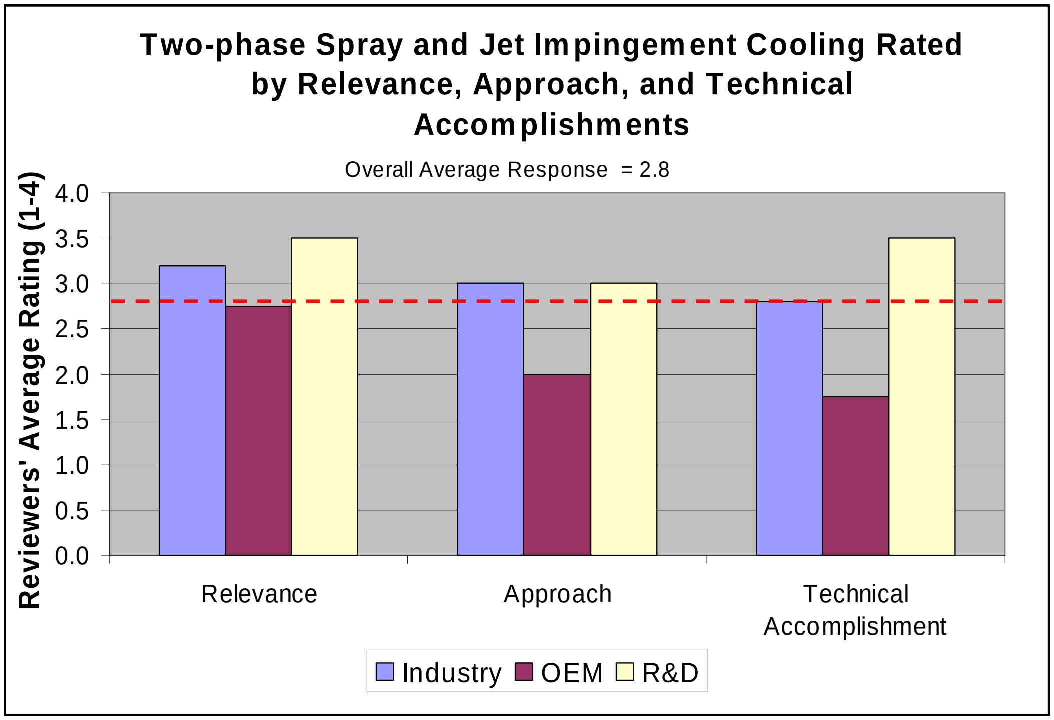
OEM Comments:
- Need to address I/O issues, challenges in getting power into and out of container
- Want to make cost comparisons with other technologies
- Not sufficient data to prove can work in a vehicle
- Project won’t contribute to knowledge base or meet goals
- Design may be impractical for automotive needs

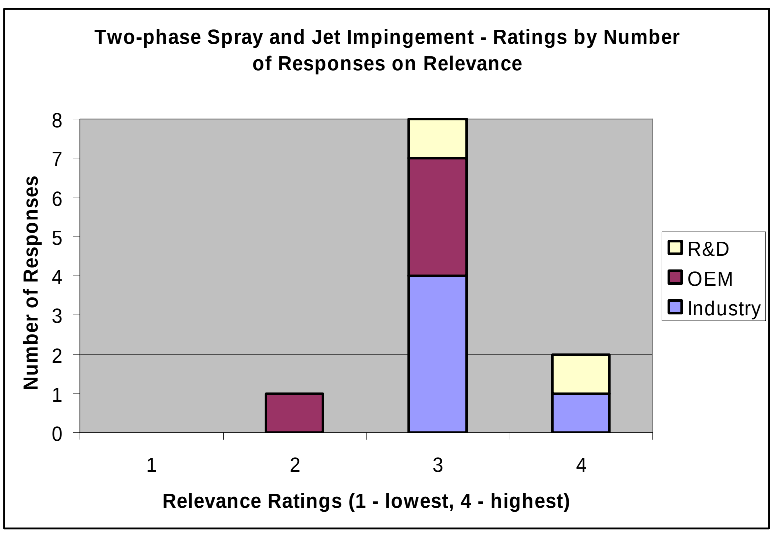
R&D Comments:
- Innovative system, prototype exhibits excellent power density
- One reviewer didn’t understand can operate system independently of AC system
- ‘Good design approach’, ‘excellent progress’, ‘interesting approach’, great deal of useful work accomplished
- Need fundamental studies performed on TM system
- Question from reviewer who lacked project background about fluid compatibility issues addressed in previous year coolant study

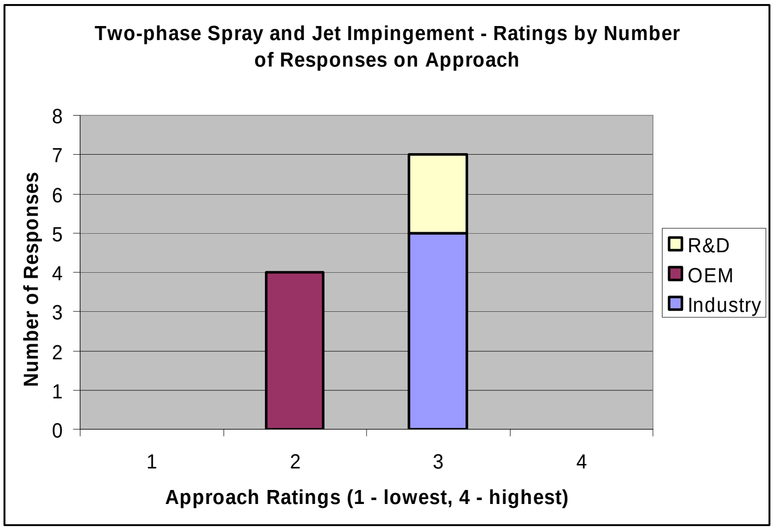
Two Phase Spray and Jet Impingement Cooling
Sreekant Narumanchi - NREL

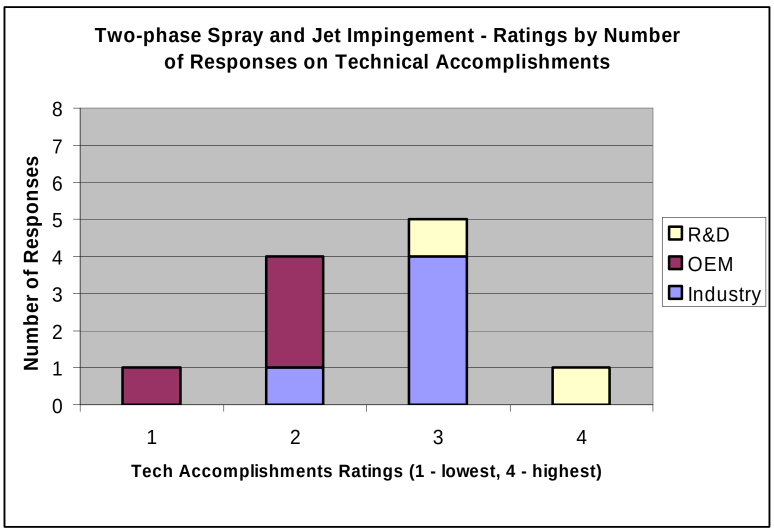
Project Summary: FY06 was the second year for this project. The objective of this project is to increase the heat removal from the IGBTs by increasing the heat transfer coefficient between the base plate and the coolant fluid. By increasing the heat transfer coefficient, a coolant temperature of 105°C can be used to cool the inverter electronics. This project will address one of the important targets of APEEM program which is the use of coolant at 105°C and enhance the heat removal from power electronics. Specific goals of this project are characterize the performance of liquid jet and spray impingement cooling of automotive power electronics; establish a liquid cooling solution which dissipates 200 to 250 W/cm2 from the silicon die in the IGBT package; demonstrate the use of glycol-water mixture at 105°C inlet temperature in the single-phase regime; and maintain the maximum temperature in the silicon die below 125°C. The first phase of this project (beginning in FY05 and leading into FY06) focuses primarily on developing models of two-phase flow and jet impingement cooling. In latter half of FY06 we began experimental tests of self-oscillating jets. In FY07 we will be collecting experimental data from two-phase sprays and jets and will begin to evaluate the system integration issues of these technologies.

Charts summarizing reviewers’ ratings and reviewers’ comments are shown below.


Two-phase Spray and Jet Impingement Cooling Rated by Relevance, Approach, and Technical Accomplishments
Overall Average Response = 2.8
Reviewers' Average Rating (1-4)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Relevance
Approach
Technical Accomplishment
Industry
OEM
R&D


Two-phase Spray and Jet Impingement - Ratings by Number of Responses on Relevance
Number of Responses
8
7
6
5
4
3
2
1
0
1
2
3
4
Relevance Ratings (1 - lowest, 4 - highest)
R&D
OEM
Industry





<u>Industry Comments:</u>

- Many more issues to consider using single phase (oscillating) jets and jet spray
- Need to evaluate cost and complexity, coefficient of performance system integration issues, reliability
- Need to include coefficient of performance
- Identify time line when the various jet spray methods can be down-selected.
- Results are useful contribution
- Spray and two phase cooling (either refrigerant or WEG) hold promise of superior heat removal
- Modeling gives an idea of which techniques hold sufficient hope for success
- Needs measured data

<u>OEM Comments:</u>

- Modeling could be valuable to OEMs, specifically 2-phase cooling
- This could be a great project, need to see more detailed modeling and data on 2-phase cooling

- Jet impingement has been seen many times before
- More detail is needed in the modeling to better explain and predict cooling
- A complete understanding of 2-phase cooling would be beneficial

R&D Comments:
- Spray cooling is one of the more promising techniques for providing significant cooling of power electronics
- Has good chance of meeting FreedomCAR goals
- Focus on both single & double phase jets, along with self oscillating jets is good
- Substantial modeling has been done
- Examination of heat transfer coefficient vs. distance and nozzle type is excellent
- Technology like this is required to reach FreedomCAR goals
- Need to address key packaging issues
- Plenty of data in the literature about jet impingement
- The simulations are good, innovative and useful; excellent experimental facilities established for academic testing
- Simulations are important contribution; work with self-oscillating jets is significant

Other Review Feedback

Questionnaires were given to each review participant to evaluate the overall review process. Numeric scores were given to a series of questions and the opportunity was given to provide additional comments. A summary of the questionnaire results is provided in Appendix F.

To assist DOE in defining power electronics and electric machines (PEEM) technology needs for plug-in hybrid electric vehicle (PHEV) applications, participants were asked for input based on their knowledge of PHEV applications and the projects that were presented at the Review. A summary of the results is provided in Appendix G.

Appendix A – Agenda

AGENDA

DOE FreedomCAR and Vehicle Technologies Program
2006 Annual Review of
Advanced Power Electronics and Electric Machines

Pollard Technology Conference Center, Oak Ridge, Tennessee
August 15-17, 2006

Tuesday - August 15, 2006

7:30 Registration and Continental Breakfast .... Lobby

8:30 Welcome .... Ted Fox (ORNL)

8:40 Introduction and Overview of the FCVT Advanced Power Electronics & Electric Machines (APEEM) Program Review........ Susan Rogers (DOE)

9:00 Overview of DOE FCVT APEEM R&D Strategy........ Mitch Olszewski (ORNL)

9:40 Break

Electric Machines

10:00 Overview of FY06 Electric Machines/Permanent Magnets/Systems Activities........ Laura Marlino (ORNL)
10:25 Interior Permanent Magnet Reluctance Machines .... John Hsu (ORNL)
- Reluctance Interior Permanent Magnet 6,000 rpm Machine
- Reluctance Permanent Magnet 16,000 rpm Machine with Brushless Field Excitation

10:55 Flux Weakening and CPSR Enhancement Techniques .... John McKeever (ORNL)
- Extending the CPSR of Synchronous Reluctance Traction Drive Motor
- Control of Fractional Slot Motors Made with Concentrated Windings

11:25 Uncluttered CVT Machine........ John Hsu (ORNL)
11:55 Advanced Traction Motor Development........ Josh Ley (UQM)

12:25 Working Lunch .... Lobby

1:40 Development of Improved Powder for Bonded Permanent Magnets........ Iver Anderson (AMES)

Systems

2:10 Fully Integrated HEV Traction Motor Development Using Thermoelectrics and Film Capacitor Innovations .... Curt Ayers (ORNL)
2:40 Benchmarking of Competitive Technologies/Component Characterization........ Bob Staunton/Larry Seiber (ORNL)

3:25 Break

3:40 Electric Machines/Permanent Magnets/Systems Wrap-Up and Preview of Next Year .... Laura Marlino (ORNL)
3:55 Open Discussion with Presenters .... Laura Marlino
Mitch Olszewski (ORNL)
Susan Rogers (DOE)

4:15 Adjourn

Wednesday - August 16, 2006

8:00	*Continental Breakfast*	*Lobby*
8:30	Welcome and Introductory Remarks	Susan Rogers (DOE)

Power Electronics

8:35	Overview of FY06 Power Electronics Activities	Laura Marlino (ORNL)
9:00	Wide Bandgap Materials	Burak Ozpineci (ORNL)
9:30	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci (ORNL)
10:00	*Break*	
10:15	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su (ORNL)
10:45	Advanced Converter Systems for High Temperature (Air cooling) HEV Environments	Leon Tolbert (ORNL)
11:15	DC to DC Converter for Fuel Cell and Hybrid Vehicles	Lizhi Zhu (Ballard)
11:45	High Temperature (105°) Inverter Development	John Mookken (Semikron)
12:15	Power Electronics Wrap-Up and Preview of Next Year	Laura Marlino (ORNL)
12:30	*Working Lunch*	*Lobby*

Capacitor Development

1:45	Overview of FY06 Capacitor Development Activities	Jean Montemarano (NSWCCD)
2:10	Embedded Capacitors for Power Electronic Systems	David Kaufman (ANL)
2:40	Glass Dielectric Capacitors	Mike Lanagan (PSU)
3:*10*	*Break*	
3:25	Polymer Film and Nano-Dielectric Capacitors	Bruce Tuttle (SNL)
3:55	Characterization of Capacitor Materials	Andy Wereszczak (ORNL)
4:25	Capacitor Development Wrap-Up and Preview of Next Year	Jean Montemarano (NSWCCD)
4:40	Open Discussion with Presenters	Jean Montemarano (NSWCCD) Susan Rogers (DOE) Laura Marlino Mitch Olszewski (ORNL)
5:*10*	*Adjourn*	

Thursday - August 17, 2006

8:00	*Continental Breakfast*	*Lobby*
8:30	Welcome and Introductory Remarks	Susan Rogers (DOE)

Thermal Control

8:35	Overview of FY06 Thermal Control Activities	Kenneth Kelly (NREL)
9:00	Identifying the Barriers and Approaches to Achieving High Temperature Coolants	Bob Staunton (ORNL)
9:30	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers (ORNL)
10:00	*Break*	
10:15	Advanced Thermal Interface Materials to Reduce Thermal Resistance	Sreekant Narumanchi (NREL)
10:45	Air Cooling for Power Electronics	Desikan Bharathan (NREL)
11:15	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi (NREL)
11:45	Dynamic and Steady State Modeling to Identify, Over Various Drive Cycles, Component and System Performance Efficiency and Thermal Loads	Michael O'Keefe (NREL)
12:15	*Working Lunch*	*Lobby*
1:30	Low Thermal Resistance IGBT Structure	Keith Gawlik (NREL)
2:00	Carbon Foam Thermal Management Materials	Nidia Gallego (ORNL)
2:30	*Break*	
2:45	Thermal Control Wrap-Up and Preview of Next Year	Kenneth Kelly (NREL)
3:00	Open Discussion with Presenters	Kenneth Kelly (NREL) Susan Rogers (DOE) Mitch Olszewski (ORNL)
3:30	Programmatic Topics and Summary	Susan Rogers (DOE)
3:45	*Adjourn*	
3:50	Closed Meeting with DOE Team and Reviewers	
5:00	*Adjourn Closed Meeting*	

Appendix B – Attendance Listing

DOE FREEDOMCAR AND VEHICLE TECHNOLOGIES PROGRAM
ADVANCED POWER ELECTRONICS AND ELECTRICAL MACHINES

Total Attendees = 111
Attended in person = 104
Attended via Webcast = 7

Attended in person:

1. Donald Adams–Oak Ridge National Laboratory; National Transportation Research Center, 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 865-946-1321; Fax: 865-946-1262; Email: adamsdj@ornl.gov

2. Iver Anderson–Ames Laboratory; Iowa State University; 222 Metals Development Building, Ames, Iowa 50011-3020; Ph: 515-294-9791; Fax: 515-294-8727; Email: andersoni@ameslab.gov

3. Curtis Ayers–Oak Ridge National Laboratory; National Transportation Research Center, 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 865-946-1342; Fax: 865-946-1262; Email: ayerscw@ornl.gov

4. Tolga Aytug–Oak Ridge National Laboratory; P.O. Box 2008, MS-6061, Oak Ridge, TN 37831-6061; Ph: 865-574-6271; aytugt@ornl.gov

5. J. Milton Bailey–Oak Ridge National Laboratory; National Transportation Research Center, 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 865-946-1324; 865-946-1262; Email: jmbail@utk.edu

6. U. Balu Balachandran–Argonne National Laboratory; Argonne, IL, Ph: 630-252-4250; Fax: 630-252-3604; Email balu@anl.gov

7. Fred Barlow–University of Idaho (recently moved from the University of Arkansas; Email: fbarlow@uark.edu).

8. Desikan Bharathan–National Renewable Energy Laboratory; 1617 Cole Boulevard; Golden, CO 80401; Ph: 303-887-4215; Fax: 312-235-3703; Email: Desikan_Bharathan@nrel.gov

9. Timothy A. Burress–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 946-1385; Fax: 946-1262; Email: burressta@ornl.gov

10. Jeremy Campbell–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 946-1532; Fax: 946-1262; Email: campbelljb@ornl.gov

11. Steven L. Campbell–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 946-1485; Fax: 946-1262; Email: campbellsl@ornl.gov

12. John N. Chiasson–Boise State University; ECE Department; 1910 University Drive; Boise, Idaho 83725; Email: johnchiasson@boisestate.edu

13. Madhu S. Chinthavali–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 865-946-1411; Fax: 865-946-1262; Email: chinthavalim@ornl.gov

14. David Christen–Oak Ridge National Laboratory; P.O. Box 2008, MS-6061, Oak Ridge, TN 37831-6061; Ph: 865-574-6269; Email: christendk@ornl.gov

15. Denis Colahan–NSWC-Phila; 1000 Kitty Hawk Avenue, Philadelphia, PA 19112; Ph: 215-897-7231; Fax: 215-897-8380; Email denis.colahan@navy.mil

16. James W. Connell–Advanced Thermal Technologies, LLC; Upton, MA 01568; Ph: 508-529-4413; Email: jconnell@charter.net

17. Chester Coomer–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 946-1318; Fax: 946-1400; Email: coomercl@ornl.gov

18. P. Steven Cooke–U.S. DOE National Energy Technology; Morgantown, WV 26505; Ph: 305-285-5437; Fax: 304-285-4403; Email steve.cooke@netl.doe.gov

19. Joeseph P. Cunningham–Oak Ridge National Laboratory; P.O. Box 2008, MS-6054, Oak Ridge, TN 37831-6054; Ph: 865-576-4778; Email: cunninghamjp@ornl.gov

20. Jan Draine–Oak Ridge National Laboratory; National Transportation Research Center, 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 865-946-1337; Fax 864-946-1262; Email: drainjm@ornl.gov

21. Tien Q. Duong–U.S. Department of Energy; 1000 Independence Avenue, Forrestal Building, EE-2G; Washington, D.C. 20585; Ph: 202-586-2210; Email: Tien.Duong@ee.doe.gov

22. Ayman M. F. El-Refaie–GE Global Research; 1 Research Circle; Niskayuna, NY 12309-1027; Ph: 518-387-6660; Fax: 518-387-6675; Email: elrefaie@research.ge.com

23. Mehmet Ertugrul–Oak Ridge National Laboratory; P.O. Box 2008, MS-6061, Oak Ridge, TN 37831-6061; Ph: 865-574-6270; Email: ertugrulm@ornl.gov

24. Karl F. Fiegenschuh–Ford Motor Company; Dearborn, MI 28121; Ph: 313-337-3125; Fax: 313-337-3125; Email: kfiegens@ford.com

25. Edward Fox–¬Oak Ridge National Laboratory; P.O. Box 2008, MS-6248, Oak Ridge, TN 37831-6248; Ph: 865-574-9599; email: foxec@ornl.gov

26. Douglas W. Freitag–Dow Corning Corporation; 21159 New Hampshire Avenue, Brookeville, MD 20833; Ph: 301-570-3821; Fax: 301-570-3836; Email dfreitag@baysidematerials.com

27. David A. Fulton–Remy, Inc.; Anderson, IN 46013; Ph: 765-778-6709; Fax: 765-778-6644; Email fulton.david@remyinc.com

28. Nidia Gallego–Oak Ridge National Laboratory; P.O. Box 2008, MS-6087, Oak Ridge, TN 37831-6087; Ph: 865-241-945957; email: gallegonc@ornl.gov

29. Kathy Gambrell–Oak Ridge National Laboratory; National Transportation Research Center, 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 865-946-1286; Fax 864-946-1262; Email: gambrellkp@ornl.gov

30. Vijay K. Garg–Ford Motor Company; Dearborn, MI 48121; Ph: 313-390-2807; Fax: 313-337-5581; Email vgarg@ford.com

31. Keith Gawlik–National Renewable Energy Laboratory; Golden, CO; Ph: 303-384-7515; Fax: 303-384-7540; Email: keith_gawlik@nrel.gov

32. Jerry L. Gibbs–U.S. DOE/FCVT; Washington, D.C. 20585; Ph: 303-586-1182; Fax: 202-586-1600; Email: jerry.gibbs@ee.doe.gov

33. Steven S. Golik–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 946-1411; Fax: 946-1262; Email: golikss@ornl.gov

34. Graham Hagey–Sentech, Inc.; 7475 Wisconsin Ave. Suite 900; Bethesda, MD 20814; Ph: 231 347 4468; Fax: 231-347-4468; Email: grahamhagey@charter.net

35. Keith S. Hardy–Argonne National Laboratory; Argonne, IL 60439; Ph: 630-816-7383; Fax: 630-252-3443: Email: khardy@anl.gov

36. Robert A. Hawsey–Oak Ridge National Laboratory; P.O. Box 2008, MS-6195, Oak Ridge, TN 37831-6195; Ph: 865-574-8057; email: hawseyra@ornl.gov

37. Monty Hayes–Delphi Electronics and Safety; P.O. Box 9005, M/C D35; Kokomo, Indiana 46904-9005; Ph: 765 451 3; Fax: 765-; Email: monty.b.hayes@delphi.com

38. John Hsu–Oak Ridge National Laboratory; National Transportation Research Center, 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 865-946-1325; Fax: 865-946-1262; Email: hsujs@ornl.gov

39. Patricia C. Irwin–GE Global Research; Schenectady, NY 12309; Ph: 518-387-7198; Fax: 518-387-7006; Email: irwinpc@crd.ge.com

40. Syed Islam–University of Tennessee-Knoxville/Oak Ridge National Laboratory; Email: islamsk@ornl.gov

41. George John–General Motors; Torrance, CA 90505; Ph: 310-257-3697; Fax: 310-257-3729; Email: george.john@aol.com

42. W. Keith Kahl–Oak Ridge National Laboratory; National Transportation Research Center, 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 865-946-1203; Fax: 865-946-1214; Email: kahlwk@ornl.gov

43. David Kaufman–Argonne National Laboratory; 9700 S. Cass Avenue; Argonne, IL 60439; Ph: 630 252-4251; Fax: 630-252-4289; Email: david.kaufman@anl.gov

44. Kenneth J. Kelly–National Renewable Energy Laboratory; Golden, CO 80401; Ph: 303-275-4465; Fax: 303-275-4415; Email: kenneth_kelly@nrel.gov

45. T. Suang Khuwatsamrit–EVAmerica; Bogart, GA 30622; Ph: 706-552-1522; Fax: 706-552-1524; Email: suang@evamerica.us

46. Edward A. Knoth–IAP Research, Inc.; Dayton, OH 45429; Ph: 937-296-1806; Fax: 937-296-1114; Email: Ed.Knoth@iap.com

47. Dennis A. Kramer–ArvinMeritor, Inc.; Troy, MI 48084; Ph: 248-435-1712; Fax: 248-435-3545; Email: dennis.kramer@arvinmeritor.com

48. Jason Lai–Virginia Polytechnic Institute & State University; The Bradley Department of Electrical Engineering; Virginia Power Electronics Center; Blacksburg, Virginia 24061-0111; Ph: 540 231 4741; Fax: 540-231-3362; Email: laijs@vt.edu

49. Michael Lanagan–Pennsylvania State University; Engineering Science and Mechanics; 0278 Materials Research Laboratory; University Park, PA 16801; Ph: 814-865-6992; Fax: 814-865-2326; Email: mlanagan@psu.edu

50. A. J. Lasley–Delphi Corporation; Kokomo, IN 46902; Ph: 765 451 3875; Fax: 765-451-3690; Email: a.j.lasley@delphi.com

51. SeongTaek Lee–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 946-1488; Fax: 946-1262; Email: leest@ornl.gov

52. Josh Ley–UQM Technologies, Inc.; Frederick, CO; Ph: 303-273-2002, ext. 1152; Fax: 303-278-7007; Email: jley@uqm.com

53. Michael Lloyd–Energetics, Inc.; 7164 Columbia Gateway Drive; Columbia, MD 21046; Ph: 410 953 6245; Fax: 410-290-0377; Email: mlloyd@energetics.com

54. Brad Lucas–Shin-Etsu Magnetics Inc.; Glen Ellyn, IL 60540; Ph: 630 858-9340; Fax: 630-858-9341; Email: brad@smisj.com

55. Jon Lutz–UQM Technologies, Inc.; 7501 Miller Drive; Frederick, CO 80530; Ph: 303-278-2002; Fax: 303 278-7007; Email: jlutz@uqm.com

56. Beihai Ma–Argonne National Laboratory; Argonne, IL 60439; Ph: 630-252-9961; Fax: 630-252-8604; Email: bma@anl.gov

57. Laura Marlino–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard; Knoxville, TN 37932; Ph: 865-946-1245; Fax: 865-946-1262; marlinold@ornl.gov

58. Michael Mazzola–SemiSouth Laboratories, Inc.; 201 Research Boulevard; Starkville, MS 39759; Ph: 662 324-7607, ext. 34; Fax: 662-324-7997; Email: mike.mazzola@semisouth.com

59. F. Patrick McCluskey–University of Maryland; Department of Mechanical Engineering; Rm. 2181, Martin Hall #88; College Park, MD 20742; Ph: 301-405-0279; Fax: 301-314-9477; Email: mcclupa@eng.umd.edu

60. John McKeever–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard; Knoxville, TN 37932; Ph: 865-946-1316; Fax: 865-946-1262; mckeeverjw@ornl.gov

61. Mark Mehall–Ford Motor Company, Research & Advanced Engineering; Scientific Research Laboratory, Mail Drop 2247, Room 3317; 2101 Village Road; Dearborn, MI 48124; Phone and Fax 313-323-2064; Email: mmehall@ford.com

62. Michael Melfi–Rockwell Automation; 26391 Curtiss Wright Parkway, Suite 102; Richmond Heights, OH 44143; Ph: 216-261-3644, ext. 223; Fax: 216-261-3887; Email: mjmelfi@powersystems.rockwell.com

63. John W. Meyer–General Motors; 7601 East 88th Place, Indianap9olis, IN 46256; Ph: 317-915-2875; Fax: 317-95-2703; Email: john.meyeriii@gm.com

64. John M. Miller–Maxwell Technologies, Inc.; San Diego, CA 92123; Ph: 858-503-3383; Fax: 858-503-3301; Email: jmiller@maxwell.com

65. Jean A. Montemarano–Naval Surface Warfare Center, Carderock Division; Code 642, NSWCD, 9500 MacArthur Boulevard; West Bethesda, Maryland 20817; Ph: 301-227-4964; Fax: 301-227-4814; Email: jeanmonte@comcast.net

66. John Mookken–Semikron USA, Inc.; 11 Executive Dr.; Hudson, NH 03051; Ph: 603-883-8102; Fax: 603-883-8021; Email: john.mookken@semikron.com

67. Sreekant Narumanchi–National Renewable Energy Laboratory; 1617 Cole Boulevard; Golden, CO 80401-3393; Ph: 303-275-4062; Fax: 303-275-4415; Email: sreekant_narumanchi@nrel.gov

68. Samuel Nelson–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard; Knoxville, TN 37932; Ph: 865-946-1327; Fax: 865-946-1262; nelsonscjr@ornl.gov

69. Michael P. O'Keefe–National Renewable Energy Laboratory; Golden, CO 80401; Ph: 303-275-4268; Fax: 303-275-4415; Email: michael_okeefe@nrel.gov

70. Mitch Olszewski–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard; Knoxville, TN 37932; Ph: 865-946-1350; Fax: 865-946-1262; olszewskim@ornl.gov

71. Pam Olszewski–Oak Ridge National Laboratory; National Transportation Research Center, 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 865-946-1317; Fax: 865-946-1262; Email: olszewskipj@ornl.gov

72. Pedro Otaduy–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard; Knoxville, TN 37932; Ph: 865-946-1344; Fax: 865-946-1262; otaduypj@ornl.gov

73. Burak Ozpineci–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard; Knoxville, TN 37932; Ph: 865-946-1329; Fax: 865-946-1262; ozpinecib@ornl.gov

74. Parans Paranthaman–¬Oak Ridge National Laboratory; P.O. Box 2008, MS-6100, Oak Ridge, TN 37831-6100; Ph: 865-574-5045; email: paranthamanm@ornl.gov

75. Niranjan Patil–Oak Ridge National Laboratory/UTK; National Transportation Research Center; 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 946-1488; Fax: 946-1262; Email: patilna@ornl.gov

76. Billy W. Peace–AVX Corporation; 801 17th Avenue, South; Myrtle Beach, South Carolina 29578; Ph: 843 946-0440; Fax: 843-916-7765; Email: bpeace@avxus.com

77. Fang Z. Peng–Michigan State University; 2120 Engineering Building; East Lansing, Michigan 48824; Ph: 517-336-4687; Fax: 517-353-1980; Email: fzpeng@msu.edu

78. Terry Penney–National Renewable Energy Laboratory; Golden, CO 80401; Ph: 303-275-4434; Fax: 303-275-4415; Email: terry_penney@nrel.gov

79. Todd A. Polley–nGimat Company; Chamblee, GA 30341; Ph: 678-287-3913; Fax: 678-287-3997; Email: tpolley@ngimat.com

80. Duane P. Prusia–PowerEx, Inc.; Youngwood, PA 15697; Ph: 724-925-4402; Fax: 724-925-4393; Email: dprusia@pwrx.com

81. Larry Radosevich–Rockwell Automation; Mequon, WI 53092; Ph: 262-512-2366; Fax: 262-512-2092; Email: ldradosevich@ra.rockwell.com

82. Susan Rogers–U.S. Department of Energy; Office of FreedomCAR and Vehicle Technologies; 1000 Independence Avenue, Forrestal Building, EE-2G; Washington, D.C. 20585; Ph: 202-586-8997; Email: susan.rogers@ee.doe.gov

83. Joseph K. Scharrer–Rotordynamics-Seal Research; Loomis, CA 95650; Ph: 916-660-0444, ext. 12; Fax: 916-660-0222; Email: rsr@rsr.com

84. Larry Seiber–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard; Knoxville, TN 37932; Ph: 865-946-1334; Fax: 865-946-1262; seiberle@ornl.gov

85. Timothy A. Shedd–University of Wisconsin; Madison, WI 53706; Ph: 608-265-2930; Fax: 608-262-8264; Email: shedd@engr.wisc.edu

86. Ashely R. Smith–Sentech, Inc.; 700 S. Illinois Ave., Suite A-201; Oak Ridge, TN 37830; Ph: 865 483 0359 ext. 103; Fax: 865-483-0439; Email: asmith@sentech.org

87. David Smith–Sentech, Inc.; 700 S. Illinois Ave., Suite A-201; Oak Ridge, TN 37831; Ph: 865 483 0359 ext. 105; Fax: 865-483-0439; Email: dsmith@sentech.org

88. Gregory S. Smith–General Motors; 3050 Lomita Boulevard, Torrance, CA 90505; Ph: 310-257-3812; Fax: 310-257-3777; Email: gregory.3.smith@gm.com

89. Richard Smith–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard; Knoxville, TN 37932; Ph: 865-803-1517; smithrl4@ornl.gov

90. Wen L. Soong–University of Adelaide; Adelaide, South Australia 5005; Ph: 608-265-3816; Fax: 608-262-5559; Email: wlsoong@eleceng.adelaide.edu.au

91. Robert Staunton–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard; Knoxville, TN 37932; Ph: 865-946-1351; Fax: 865-946-1262; stauntonrh@ornl.gov

92. David Stinton–Oak Ridge National Laboratory; P.O. Box 2008, MS-6065, Oak Ridge, TN 37831-6065, Ph: 865-574-4556, Email: stintondp@ornl.gov

93. Gui-Jia Su–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard; Knoxville, TN 37932; Ph: 865-946-1330; Fax: 865-946-1262; Email sugj@ornl.gov

94. Rogelio A. Sullivan U.S. Department of Energy; Office of FreedomCAR and Vehicle Technologies; 1000 Independence Avenue, Forrestal Building, EE-2G; Washington, D.C. 20585; Ph: 202-586-8042; Email: Rogelio.sullivan@ee.doe.gov

95. Lixin Tang–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 946-1526; Fax: 946-1262; Email: lixint@ornl.gov

96. Ralph Taylor–Delphi Electronics and Safety; 2705 S. Goyer Road; Kokomo, Indiana 46904; Ph: 765 451 3884; Fax: 765-451-3879; Email: Ralph.S.Taylor@Delphi.com

97. Leon Tolbert–Oak Ridge National Laboratory; National Transportation Research Center; 2360Cherahala Boulevard; Knoxville, TN 37932; Ph: 865-946-1332; Fax: 865-946-1262; tolbertlm@ornl.gov

98. Bruce Tuttle–Sandia National Laboratories; Albuquerque, NM 87185; Phone: 505-845-8026; Fax: 505-844-9781; Email: batuttl@sandia.gov

99. Donald Walkowicz–USCAR; Southfield, MI 48075; Ph: 248-223-9009; Fax: 248-223-9021; Email: dwalkowicz@uscar.org

100. Andrew A. Wereszczak–Oak Ridge National Laboratory; P.O. Box 2008, MS-6068, Oak Ridge, TN 37831-6068; Ph: 865-576-1169; Email: wereszczakaa@ornl.gov

101. Randy Wiles–Oak Ridge National Laboratory; National Transportation Research Center; 2360 Cherahala Boulevard, Knoxville, TN 37932; Ph: 946-1319; Fax: 946-1400; Email: wilesrh@ornl.gov

102. David L. Wilson–Freescale Semiconductor; 325 N. Corporate Drive, Suite 220; Brookfield, WI 53045; Ph: 262-679-9302; Fax: 262-792-3955; Email: david.l.wilson@freescale.com

103. Richard Ziegler –Sentech, Inc.; 700 S. Illinois Ave., Suite A-201; Oak Ridge, TN 37831; Ph: 865 483 0359; Fax: 865-483-0439; Email: Rziegler@sentech.org

104. Lizhi Zhu–Ballard Power Systems; 15001 Commerce Drive North; Dearborn, Michigan 48188; Ph: 313 354 5973; Fax: 313-583-5990; Email: lizhi.zhu@ballard.com

Attended via Webcast:

1. Terrence Burke–U.S. Army TARDEC, AMSRD-TAR-R; Warren, MI 48397-5000; Ph: 586-574-6816; Fax: 586-574-5054; Email: BurkeTe@tacom.army.mil

2. Bhanumathi Chelluri–IAP Research; Dayton, OH 45429; Ph: 937-296-1806; Fax: 937-296-1114; Email: bhanu@iap.com

3. Matthew Kramer–Iowa State University; Ames, IA 50011; Ph: 515-294-0276; Email: mjkramer@ameslab.gov

4. Gerald McAlwee; BAE Systems; Santa Clara, CA 95050; Ph: 408-289-0189; Fax: 408-289-3938; Email: Gerald.McAlwee@baesystems.com

5. Ralph W. McCallum (Bill)–Ames Laboratory/Iowa State University; 106 Wilhelm Hal; Ames, IA 50011; Ph: 515-294-7436; Fax: 515-294-4291; Email: mccallum@ameslab.gov

6. Brian Richardson–Remy, Inc.; Anderson, IN 46013; Ph: 765-778-6347; Fax: 765-221-6137; Email: richardson.brian@remyinc.com

7. Edwin Richardson–Thomas & Skinner; Indianapolis, IN 46205; Ph: 317-923-2501; Fax: 317-924-4826; Email: erichardson@thomas-skinner.com

Appendix C – Sample Project Evaluation Form

DOE FreedomCAR and Vehicle Technologies Program
FY06 Annual Review of Advanced Power Electronics and Electric Machine Research
Sample Project Evaluation Form

TITLE OF PRESENTATION:

PRESENTER NAME: **LABORATORY/COMPANY:**

Reviewer Name:

Affiliation: ☐**DOE** ☐**National Lab** ☐**University** ☐**Government** ☐**Consultant** ☐**Supplier** ☐**OEM**

Ability to Rate Based on Expertise in this Specific Area (please circle one or fill in the number):
Not my area of expertise 1 2 3 4 5 6 7 8 9 10 Expert in this area

Research is Important to FreedomCAR (please circle one or fill in the number):
Strongly disagree 1 2 3 4 5 6 7 8 9 10 Strongly agree

*Using the following criteria, please rate the **work** presented in the context of program objectives. Please provide **specific comments** in the space provided to support your evaluation.*

1. **<u>Relevance</u>** to overall DOE objectives and mission (long-range, high-risk R&D for Advanced Power Electronics & Electric Machines) to achieve FreedomCAR goals.

4 – Outstanding. *The project is sharply focused on one or more key technical barriers to the development of advanced power electronics and electric motors.*	**Rating:** **Enter justification for rating**
3 – Good. *Most aspects of the project will contribute to significant progress in overcoming these barriers.*	
2 – Fair. *Some aspects of the project may lead to progress in overcoming some barriers.*	
1 – Poor. *The project is very unlikely to make significant contributions to overcoming the barriers.*	
Does this research have the potential to meet FreedomCAR technical targets for this area? ☐ Yes ☐ No. If no, explain why not.	

2. <u>Approach</u> to perform the R&D – degree to which technical barriers are addressed, the project is well-designed, technically feasible, and integrated with other research.

4 – Outstanding. *It is difficult for the approach to be improved significantly.*	**Rating:** **Enter justification for rating**
3 – Good. *The approach is generally well thought out and effective, but could be improved in a few areas.*	
2 – Fair. *The approach has significant weaknesses.*	
1 – Poor. *The approach is not responsive to the project objectives.*	
Is this approach sufficiently innovative? ☐ Yes ☐ No. If no, explain why not.	

3. <u>Technical Accomplishments and Progress</u> toward overall project and DOE goals – the degree to which research progress is measured against performance indicators and to which the project exhibits improved performance (effectiveness, efficiency, cost, and benefits).

4 – Outstanding. *The project has made excellent progress toward overcoming one or more key technical barriers to development of advanced power electronics and electric motors.*	**Rating:** **Enter justification for rating**
3 – Good. *The project has shown significant progress toward overcoming barriers.*	
2 – Fair. *The project has shown a modest amount of progress in overcoming barriers, the overall rate of progress has been slow.*	
1 – Poor. *The project has demonstrated little or no progress toward overcoming the barriers.*	
Are accomplishments and progress sufficient (at a point that would be expected)? ☐ Yes ☐ No. If no, explain why not. What, if any, significant accomplishment took place in this reporting period (describe briefly the significance of the accomplishment)?	

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional comments:

Appendix D – Summary of Reviewer Ratings

Affiliation	Title	Presenter	Ability to Rate	Important to FreedomCAR	Relevance Rating	Approach Rating	Technical Accomplishment and Progress Rating	Average Rating (1-4)
Industry	Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments	Leon Tolbert	5	10	3	3	3	3.0
Industry	Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments	Leon Tolbert	5	9	3	2	2	2.3
Industry	Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments	Leon Tolbert	5	10	4	4	4	4.0
Industry	Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments	Leon Tolbert	8	9	4	4	3	3.7
Industry	Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments	Leon Tolbert	9	9	3	4	3	3.3
Industry	**Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**							**3.3**
OEM	Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments	Leon Tolbert	5	8	3	3	3	3.0
OEM	Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments	Leon Tolbert	5	7	4	3	3	3.3
OEM	Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments	Leon Tolbert	7	10	3	3	3	3.0
OEM	Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments	Leon Tolbert	8	6	3	4	3	3.3
OEM	**Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**							**3.2**
R&D	Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments	Leon Tolbert	10	9	3	3	2	2.7
R&D	Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments	Leon Tolbert	9	8	4	3	3	3.3
R&D	**Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**							**3.0**

Industry	Advanced Thermal Interface Materials to Reduce Thermal Resistance	Sreekant Narumanchi	1	5	2	3	3	2.7
Industry	Advanced Thermal Interface Materials to Reduce Thermal Resistance	Sreekant Narumanchi	6	6	2	3	3	2.7
Industry	Advanced Thermal Interface Materials to Reduce Thermal Resistance	Sreekant Narumanchi	7	6	2	2	2	2.0
Industry	Advanced Thermal Interface Materials to Reduce Thermal Resistance	Sreekant Narumanchi	9	10	4	3	3	3.3
Industry	**Advanced Thermal Interface Materials to Reduce Thermal Resistance**							**2.7**
OEM	Advanced Thermal Interface Materials to Reduce Thermal Resistance	Sreekant Narumanchi	5	7	1	2	2	1.7
OEM	Advanced Thermal Interface Materials to Reduce Thermal Resistance	Sreekant Narumanchi	5	2	2	2	2	2.0
OEM	Advanced Thermal Interface Materials to Reduce Thermal Resistance	Sreekant Narumanchi	7	8	2	2	2	2.0
OEM	Advanced Thermal Interface Materials to Reduce Thermal Resistance	Sreekant Narumanchi	8	4	1	2	2	1.7
OEM	**Advanced Thermal Interface Materials to Reduce Thermal Resistance**							**1.9**
R&D	Advanced Thermal Interface Materials to Reduce Thermal Resistance	Sreekant Narumanchi	10	3	1	2	2	1.7
R&D	Advanced Thermal Interface Materials to Reduce Thermal Resistance	Sreekant Narumanchi	2	5	2	2	3	2.3
R&D	**Advanced Thermal Interface Materials to Reduce Thermal Resistance**							**2.0**
Industry	Advanced Traction Motor Development	Josh Ley	10	9	3	3	4	3.3
Industry	Advanced Traction Motor Development	Josh Ley	9	10	4	3	3	3.3
Industry	**Advanced Traction Motor Development**							**3.3**
OEM	Advanced Traction Motor Development	Josh Ley	5	9	3	3	2	2.7
OEM	Advanced Traction Motor Development	Josh Ley	6	8	3	3	2	2.7
OEM	Advanced Traction Motor Development	Josh Ley	6	10	4	3	3	3.3
OEM	Advanced Traction Motor Development	Josh Ley	7	8	3	3	3	3.0
OEM	**Advanced Traction Motor Development**							**2.9**

R&D	Advanced Traction Motor Development	Josh Ley	2	8	3	3	3	3.0
R&D	Advanced Traction Motor Development	Josh Ley	9	9	4	3	4	3.7
R&D	**Advanced Traction Motor Development**							**3.4**
Industry	Air Cooling for Power Electronics	Desikan Bharathan	2	10	4	3	2	3.0
Industry	Air Cooling for Power Electronics	Desikan Bharathan	7	8	2	3	2	2.3
Industry	Air Cooling for Power Electronics	Desikan Bharathan	7	10	3	3	3	3.0
Industry	Air Cooling for Power Electronics	Desikan Bharathan	8	8	4	3	3	3.3
Industry	Air Cooling for Power Electronics	Desikan Bharathan	9	10	4	3	3	3.3
Industry	**Air Cooling for Power Electronics**							**3.0**
OEM	Air Cooling for Power Electronics	Desikan Bharathan	5	1	1	1	2	1.3
OEM	Air Cooling for Power Electronics	Desikan Bharathan	5	8	1	1	1	1.0
OEM	Air Cooling for Power Electronics	Desikan Bharathan	7	8	3	2	2	2.3
OEM	Air Cooling for Power Electronics	Desikan Bharathan	8	4	1	1	2	1.3
OEM	**Air Cooling for Power Electronics**							**1.5**
R&D	Air Cooling for Power Electronics	Desikan Bharathan	8	8	3	3	4	3.3
R&D	Air Cooling for Power Electronics	Desikan Bharathan	9	6	3	3	3	3.0
R&D	**Air Cooling for Power Electronics**							**3.2**
Industry	Benchmarking of Competitive Technologies/Component Characterization	Bob Staunton/Larry Seiber	10	10	4	3	3	3.3
Industry	Benchmarking of Competitive Technologies/Component Characterization	Bob Staunton/Larry Seiber	7	10	4	3	3	3.3
Industry	Benchmarking of Competitive Technologies/Component Characterization	Bob Staunton/Larry Seiber	8	9	3	3	3	3.0
Industry	**Benchmarking of Competitive Technologies/Component Characterization**							**3.2**
OEM	Benchmarking of Competitive Technologies/Component Characterization	Bob Staunton/Larry Seiber	6	10	4	3	3	3.3
OEM	Benchmarking of Competitive Technologies/Component Characterization	Bob Staunton/Larry Seiber	7	10	4	3	3	3.3
OEM	Benchmarking of Competitive Technologies/Component Characterization	Bob Staunton/Larry Seiber	7	8	4	3	3	3.3
OEM	Benchmarking of Competitive Technologies/Component Characterization	Bob Staunton/Larry Seiber	Reviewer did not provide number.	Reviewer did not provide number.	3	4	3	3.3

OEM	**Benchmarking of Competitive Technologies/Component Characterization**							**3.3**
R&D	Benchmarking of Competitive Technologies/Component Characterization	Bob Staunton/Larry Seiber	10	9	4	4	3	3.7
R&D	Benchmarking of Competitive Technologies/Component Characterization	Bob Staunton/Larry Seiber	8	8	4	3	3	3.3
R&D	**Benchmarking of Competitive Technologies/Component Characterization**							**3.5**
Industry	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci	4	10	3	3	3	3.0
Industry	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci	5	6	2	2	3	2.3
Industry	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci	5	7	3	4	3	3.3
Industry	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci	7	8	4	3	4	3.7
Industry	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci	9	8	3	3	3	3.0
Industry	**Cascade Multilevel Inverter for Fuel Cell Based HEV**							**3.1**
OEM	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci	5	7	3	3	3	3.0
OEM	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci	5	8	3	3	3	3.0
OEM	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci	7	10	3	3	3	3.0
OEM	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci	8	8	3	3	3	3.0
OEM	**Cascade Multilevel Inverter for Fuel Cell Based HEV**							**3.0**
R&D	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci	10	8	4	4	3	3.7
R&D	Cascade Multilevel Inverter for Fuel Cell Based HEV	Burak Ozpineci	7	8	4	3	2	3.0
R&D	**Cascade Multilevel Inverter for Fuel Cell Based HEV**							**3.4**
Industry	DC to DC Converter for Fuel Cell and Hybrid Vehicles	Lizhi Zhu	5	10	2	3	3	2.7
Industry	DC to DC Converter for Fuel Cell and Hybrid Vehicles	Lizhi Zhu	5	9	3	3	3	3.0
Industry	DC to DC Converter for Fuel Cell and Hybrid Vehicles	Lizhi Zhu	7	6	3	3	2	2.7
Industry	DC to DC Converter for Fuel Cell and Hybrid Vehicles	Lizhi Zhu	9	9	4	3	4	3.7
Industry	**DC to DC Converter for Fuel Cell and Hybrid Vehicles**							**3.0**
OEM	DC to DC Converter for Fuel Cell and Hybrid Vehicles	Lizhi Zhu	5	9	3	4	4	3.7
OEM	DC to DC Converter for Fuel Cell and Hybrid Vehicles	Lizhi Zhu	6	8	3	4	4	3.7
OEM	DC to DC Converter for Fuel Cell and Hybrid Vehicles	Lizhi Zhu	7	10	4	4	4	4.0

OEM	DC to DC Converter for Fuel Cell and Hybrid Vehicles	Lizhi Zhu	8	6	3	4	4	3.7
OEM	**DC to DC Converter for Fuel Cell and Hybrid Vehicles**							**3.8**
R&D	DC to DC Converter for Fuel Cell and Hybrid Vehicles	Lizhi Zhu	10	10	4	4	4	4.0
R&D	DC to DC Converter for Fuel Cell and Hybrid Vehicles	Lizhi Zhu	8	8	3	4	4	3.7
R&D	**DC to DC Converter for Fuel Cell and Hybrid Vehicles**							**3.9**
Industry	Development of Improved Powder for Bonded Permanent Magnets	Iver Anderson	6	8	3	4	3	3.3
Industry	Development of Improved Powder for Bonded Permanent Magnets	Iver Anderson	6	10	4	3	4	3.7
Industry	Development of Improved Powder for Bonded Permanent Magnets	Iver Anderson	9	10	4	4	4	4.0
Industry	**Development of Improved Powder for Bonded Permanent Magnets**							**3.7**
OEM	Development of Improved Powder for Bonded Permanent Magnets	Iver Anderson	5	9	4	4	3	3.7
OEM	Development of Improved Powder for Bonded Permanent Magnets	Iver Anderson	6	10	4	4	4	4.0
OEM	Development of Improved Powder for Bonded Permanent Magnets	Iver Anderson	7	9	4	4	3	3.7
OEM	Development of Improved Powder for Bonded Permanent Magnets	Iver Anderson	Reviewer did not provide number.	Reviewer did not provide number.	4	4	3	3.7
OEM	**Development of Improved Powder for Bonded Permanent Magnets**							**3.8**
R&D	Development of Improved Powder for Bonded Permanent Magnets	Iver Anderson	7	8	4	4	3	3.7
R&D	Development of Improved Powder for Bonded Permanent Magnets	Iver Anderson	8	10	4	4	3	3.7
R&D	**Development of Improved Powder for Bonded Permanent Magnets**							**3.7**

Industry	Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…	Michael O'Keefe	1	9	4	3	4	3.7
Industry	Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…	Michael O'Keefe	10	10	4	3	3	3.3
Industry	Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…	Michael O'Keefe	7	10	2	2	Reviewer did not provide a number.	2.0
Industry	Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…	Michael O'Keefe	7	7	3	2	2	2.3
Industry	Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…	Michael O'Keefe	8	9	3	3	2	2.7
Industry	**Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**							**2.8**
OEM	Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…	Michael O'Keefe	5	7	3	2	2	2.3
OEM	Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…	Michael O'Keefe	7	6	3	2	2	2.3
OEM	Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…	Michael O'Keefe	8	5	2	1	1	1.3
OEM	Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…	Michael O'Keefe	Reviewer did not provide a number.	Reviewer did not provide a number.	2	2	1	1.7
OEM	**Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**							**1.9**
R&D	Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…	Michael O'Keefe	7	10	4	4	4	4.0
R&D	Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…	Michael O'Keefe	9	7	3	3	3	3.0
R&D	**Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**							**3.5**
Industry	Embedded Capacitor Development Activities	David Kaufman	10	10	4	4	4	4.0
Industry	Embedded Capacitor Development Activities	David Kaufman	4	8	4	3	3	3.3
Industry	**Embedded Capacitor Development Activities**							**3.7**

OEM	Embedded Capacitor Development Activities	David Kaufman	4	9	4	4	4	4.0
OEM	Embedded Capacitor Development Activities	David Kaufman	5	10	4	4	4	4.0
OEM	Embedded Capacitor Development Activities	David Kaufman	5	9	4	4	4	4.0
OEM	Embedded Capacitor Development Activities	David Kaufman	8	10	4	4	4	4.0
OEM	**Embedded Capacitor Development Activities**							**4.0**
R&D	Embedded Capacitor Development Activities	David Kaufman	10	10	4	4	3	3.7
R&D	Embedded Capacitor Development Activities	David Kaufman	9	8	3	3	2	2.7
R&D	**Embedded Capacitor Development Activities**							**3.2**
Industry	Flux Weakening and CPSR Enhancement Techniques	John McKeever	10	10	4	4	4	4.0
Industry	Flux Weakening and CPSR Enhancement Techniques	John McKeever	9	10	4	3	3	3.3
Industry	**Flux Weakening and CPSR Enhancement Techniques**							**3.7**
OEM	Flux Weakening and CPSR Enhancement Techniques	John McKeever	5	10	4	3	4	3.7
OEM	Flux Weakening and CPSR Enhancement Techniques	John McKeever	6	10	4	3	4	3.7
OEM	Flux Weakening and CPSR Enhancement Techniques	John McKeever	6	10	4	4	4	4.0
OEM	Flux Weakening and CPSR Enhancement Techniques	John McKeever	7	8	4	3	4	3.7
OEM	**Flux Weakening and CPSR Enhancement Techniques**							**3.8**
R&D	Flux Weakening and CPSR Enhancement Techniques	John McKeever	10	10	4	4	4	4.0
R&D	Flux Weakening and CPSR Enhancement Techniques	John McKeever	2	4	3	3	3	3.0
R&D	**Flux Weakening and CPSR Enhancement Techniques**							**3.5**

Industry	Fully Integrated HEV Traction Motor Development Using Thermoelectrics	Curt Ayers	7	7	2	2	2	2.0
Industry	Fully Integrated HEV Traction Motor Development Using Thermoelectrics	Curt Ayers	7	8	3	3	3	3.0
Industry	Fully Integrated HEV Traction Motor Development Using Thermoelectrics	Curt Ayers	9	10	4	3	4	3.7
Industry	**Fully Integrated HEV Traction Motor Development Using Thermoelectrics**							**2.9**
OEM	Fully Integrated HEV Traction Motor Development Using Thermoelectrics	Curt Ayers	5	8	3	3	2	2.7
OEM	Fully Integrated HEV Traction Motor Development Using Thermoelectrics	Curt Ayers	6	3	2	2	2	2.0
OEM	Fully Integrated HEV Traction Motor Development Using Thermoelectrics	Curt Ayers	7	10	3	3	3	3.0
OEM	Fully Integrated HEV Traction Motor Development Using Thermoelectrics	Curt Ayers	Reviewer did not provide a number.	Reviewer did not a provide number.	2	3	2	2.3
OEM	**Fully Integrated HEV Traction Motor Development Using Thermoelectrics**							**2.5**
R&D	Fully Integrated HEV Traction Motor Development Using Thermoelectrics		4	8	3	3	3	3.0
R&D	Fully Integrated HEV Traction Motor Development Using Thermoelectrics	Curt Ayers	8	5	2	2	2	2.0
R&D	**Fully Integrated HEV Traction Motor Development Using Thermoelectrics**							**2.5**
Industry	Glass Dielectric Capacitors	Mike Lanagan	10	10	4	4	3	3.7
Industry	Glass Dielectric Capacitors	Mike Lanagan	3	6	3	2	3	2.7
Industry	**Glass Dielectric Capacitors**							**3.2**
OEM	Glass Dielectric Capacitors	Mike Lanagan	5	7	3	2	2	2.3
OEM	Glass Dielectric Capacitors	Mike Lanagan	5	7	3	2	2	2.3
OEM	Glass Dielectric Capacitors	Mike Lanagan	7	10	3	3	2	2.7
OEM	Glass Dielectric Capacitors	Mike Lanagan	Reviewer did not provide a number.	Reviewer did not provide a number.	3	2	2	2.3
OEM	**Glass Dielectric Capacitors**							**2.4**
R&D	Glass Dielectric Capacitors	Mike Lanagan	10	8	3	3	2	2.7
R&D	Glass Dielectric Capacitors	Mike Lanagan	9	9	3	3	3	3.0
R&D	**Glass Dielectric Capacitors**							**2.9**

Industry	High Temperature Inverter Development	John Mookken	5	7	3	3	3	3.0
Industry	High Temperature Inverter Development	John Mookken	6	9	3	2	2	2.3
Industry	High Temperature Inverter Development	John Mookken	7	10	2	3	2	2.3
Industry	High Temperature Inverter Development	John Mookken	7	8	4	3	3	3.3
Industry	High Temperature Inverter Development	John Mookken	9	10	4	4	3	3.7
Industry	**High Temperature Inverter Development**							**2.9**
OEM	High Temperature Inverter Development	John Mookken	5	8	3	4	3	3.3
OEM	High Temperature Inverter Development	John Mookken	5	8	3	4	4	3.7
OEM	High Temperature Inverter Development	John Mookken	6	10	4	4	4	4.0
OEM	High Temperature Inverter Development	John Mookken	8	6	3	4	3	3.3
OEM	**High Temperature Inverter Development**							**3.6**
R&D	High Temperature Inverter Development	John Mookken	10	9	3	3	4	3.3
R&D	High Temperature Inverter Development	John Mookken	10	9	4	3	4	3.7
R&D	**High Temperature Inverter Development**							**3.5**
Industry	Identifying the Barriers and Approaches to Achieving High Temp Coolants	Bob Staunton	3	9	4	4	3	3.7
Industry	Identifying the Barriers and Approaches to Achieving High Temp Coolants	Bob Staunton	7	10	2	2	2	2.0
Industry	Identifying the Barriers and Approaches to Achieving High Temp Coolants	Bob Staunton	8	8	3	2	2	2.3
Industry	Identifying the Barriers and Approaches to Achieving High Temp Coolants	Bob Staunton	8	10	4	4	3	3.7
Industry	Identifying the Barriers and Approaches to Achieving High Temp Coolants	Bob Staunton	9	9	4	4	3	3.7
Industry	**Identifying the Barriers and Approaches to Achieving High Temp Coolants**							**3.1**
OEM	Identifying the Barriers and Approaches to Achieving High Temp Coolants	Bob Staunton	5	7	3	3	2	2.7
OEM	Identifying the Barriers and Approaches to Achieving High Temp Coolants	Bob Staunton	5	9	3	3	2	2.7
OEM	Identifying the Barriers and Approaches to Achieving High Temp Coolants	Bob Staunton	7	8	3	3	2	2.7
OEM	Identifying the Barriers and Approaches to Achieving High Temp Coolants	Bob Staunton	8	10	3	3	2	2.7
OEM	**Identifying the Barriers and Approaches to Achieving High Temp Coolants**							**2.7**

R&D	Identifying the Barriers and Approaches to Achieving High Temp Coolants	Bob Staunton	10	9	4	3	3	3.3
R&D	Identifying the Barriers and Approaches to Achieving High Temp Coolants	Bob Staunton	7	10	4	3	3	3.3
R&D	**Identifying the Barriers and Approaches to Achieving High Temp Coolants**							**3.3**
Industry	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su	10	10	4	3	3	3.3
Industry	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su	4	10	3	3	3	3.0
Industry	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su	5	5	2	4	4	3.3
Industry	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su	5	9	3	2	2	2.3
Industry	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su	7	5	2	3	3	2.7
Industry	**Integrated DC/DC Converter for Multi-Voltage Bus Systems**							**2.9**
OEM	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su	5	5	2	3	3	2.7
OEM	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su	6	5	2	3	3	2.7
OEM	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su	7	10	2	3	3	2.7
OEM	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su	8	6	2	3	3	2.7
OEM	**Integrated DC/DC Converter for Multi-Voltage Bus Systems**							**2.7**
R&D	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su	10	10	4	3	4	3.7
R&D	Integrated DC/DC Converter for Multi-Voltage Bus Systems	Gui-Jia Su	4	6	3	3	3	3.0
R&D	**Integrated DC/DC Converter for Multi-Voltage Bus Systems**							**3.4**

Industry	Interior Permanent Magnet Reluctance Machines	John Hsu	10	10	4	3	3	3.3
Industry	Interior Permanent Magnet Reluctance Machines	John Hsu	8	10	4	4	3	3.7
Industry	Interior Permanent Magnet Reluctance Machines	John Hsu	9	10	3	3	2	2.7
Industry	**Interior Permanent Magnet Reluctance Machines**							**3.2**
OEM	Interior Permanent Magnet Reluctance Machines	John Hsu	5	7	2	3	3	2.7
OEM	Interior Permanent Magnet Reluctance Machines	John Hsu	6	5	2	2	2	2.0
OEM	Interior Permanent Magnet Reluctance Machines	John Hsu	6	10	3	2	2	2.3
OEM	Interior Permanent Magnet Reluctance Machines	John Hsu	8	6	3	2	2	2.3
OEM	**Interior Permanent Magnet Reluctance Machines**							**2.3**
R&D	Interior Permanent Magnet Reluctance Machines	John Hsu	10	10	4	3	3	3.3
R&D	Interior Permanent Magnet Reluctance Machines	John Hsu	2	6	3	3	3	3.0
R&D	**Interior Permanent Magnet Reluctance Machines**							**3.2**
Industry	Low Thermal Resistance IGBT Structure	Keith Gawlik	9	10	4	4	3	3.7
Industry	Low Thermal Resistance IGBT Structure	Keith Gawlik	2	6	2	4	3	3.0
Industry	Low Thermal Resistance IGBT Structure	Keith Gawlik	7	10	3	3	3	3.0
Industry	Low Thermal Resistance IGBT Structure	Keith Gawlik	7	8	3	3	2	2.7
Industry	Low Thermal Resistance IGBT Structure	Keith Gawlik	8	10	4	3	3	3.3
Industry	**Low Thermal Resistance IGBT Structure**							**3.1**
OEM	Low Thermal Resistance IGBT Structure	Keith Gawlik	5	3	1	3	1	1.7
OEM	Low Thermal Resistance IGBT Structure	Keith Gawlik	5	7	1	3	3	2.3
OEM	Low Thermal Resistance IGBT Structure	Keith Gawlik	7	6	3	3	2	2.7
OEM	Low Thermal Resistance IGBT Structure	Keith Gawlik	8	4	1	3	1	1.7
OEM	**Low Thermal Resistance IGBT Structure**							**2.1**
R&D	Low Thermal Resistance IGBT Structure	Keith Gawlik	10					3.0
R&D	Low Thermal Resistance IGBT Structure	Keith Gawlik	10	9	4	4	4	4.0
R&D	**Low Thermal Resistance IGBT Structure**							**3.5**

Industry	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi	1	6	3	3	3	3.0
Industry	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi	7	10	3	3	3	3.0
Industry	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi	7	8	4	3	3	3.3
Industry	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi	8	8	3	3	2	2.7
Industry	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi	9	9	3	3	3	3.0
Industry	**Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**							**3.0**
OEM	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi	5	7	3	2	2	2.3
OEM	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi	5	Reviewer did not provide a number.	3	2	2	2.3
OEM	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi	7	9	3	2	2	2.3
OEM	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi	8	Reviewer did not provide a number.	2	2	1	1.7
OEM	**Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**							**2.2**
R&D	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi	10	8	4	3	4	3.7
R&D	Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling	Sreekant Narumanchi	9	8	3	3	3	3.0
R&D	**Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**							**3.4**
Industry	Polymer Film and Nano-Dielectric Capacitors	Bruce Tuttle	10	10	3	4	3	3.3
Industry	Polymer Film and Nano-Dielectric Capacitors	Bruce Tuttle	3	6	3	3	4	3.3
Industry	**Polymer Film and Nano-Dielectric Capacitors**							**3.3**
OEM	Polymer Film and Nano-Dielectric Capacitors	Bruce Tuttle	5	8	3	3	2	2.7
OEM	Polymer Film and Nano-Dielectric Capacitors	Bruce Tuttle	5	8	3	3	2	2.7
OEM	Polymer Film and Nano-Dielectric Capacitors	Bruce Tuttle	8	5	3	3	2	2.7
OEM	**Polymer Film and Nano-Dielectric Capacitors**							**2.7**

R&D	Polymer Film and Nano-Dielectric Capacitors	Bruce Tuttle	9	9	4	3	3	3.3
R&D	Polymer Film and Nano-Dielectric Capacitors	Bruce Tuttle	9	9	4	3	3	3.3
R&D	**Polymer Film and Nano-Dielectric Capacitors**							**3.3**
Industry	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers	2	6	2	3	4	3.0
Industry	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers	7	10	3	3	3	3.0
Industry	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers	8	9	3	2	2	2.3
Industry	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers	9	10	4	3	3	3.3
Industry	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers	Reviewer did not provide a number.	9	4	4	4	4.0
Industry	**Thermal Control for Inverters and Motors**							**3.1**
OEM	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers	5	2	1	1	2	**1.3**
OEM	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers	5	8	2	1	2	1.7
OEM	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers	7	7	3	2	2	2.3
OEM	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers	8	5	1	1	2	1.3
OEM	**Thermal Control for Inverters and Motors**							**1.7**
R&D	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers	7	5	2	3	3	2.7
R&D	Thermal Control for Inverters and Motors	John Hsu/Curt Ayers	8	10	4	3	4	3.7
R&D	**Thermal Control for Inverters and Motors**							**3.2**
Industry	Uncluttered CVT Machines	John Hsu	10	10	4	4	3	3.7
Industry	Uncluttered CVT Machines	John Hsu	9	10	2	2	2	2.0
Industry	**Uncluttered CVT Machines**							**2.9**
OEM	Uncluttered CVT Machines	John Hsu	5	2	1	1	1	1.0
OEM	Uncluttered CVT Machines	John Hsu	5	10	2	2	2	2.0
OEM	Uncluttered CVT Machines	John Hsu	6	5	2	2	1	1.7
OEM	Uncluttered CVT Machines	John Hsu	8	3	2	2	1	1.7
OEM	**Uncluttered CVT Machines**							**1.6**
R&D	Uncluttered CVT Machines	John Hsu	2	8	3	3	3	3.0
R&D	Uncluttered CVT Machines	John Hsu	7	9	4	4	2	3.3
R&D	**Uncluttered CVT Machines**							**3.2**

Industry	Wide Bandgap Materials	Burak Ozpineci	5	9	3	3	3	3.0
Industry	Wide Bandgap Materials	Burak Ozpineci	5	10	4	4	4	4.0
Industry	Wide Bandgap Materials	Burak Ozpineci	6	10	3	3	3	3.0
Industry	Wide Bandgap Materials	Burak Ozpineci	9	10	4	3	4	3.7
Industry	Wide Bandgap Materials	Burak Ozpineci	9	10	4	4	4	4.0
Industry	**Wide Bandgap Materials**							**3.5**
OEM	Wide Bandgap Materials	Burak Ozpineci	5	10	4	4	4	4.0
OEM	Wide Bandgap Materials	Burak Ozpineci	5	8	4	4	4	4.0
OEM	Wide Bandgap Materials	Burak Ozpineci	6	10	4	4	4	4.0
OEM	Wide Bandgap Materials	Burak Ozpineci	8	10	4	4	4	4.0
OEM	**Wide Bandgap Materials**							**4.0**
R&D	Wide Bandgap Materials	Burak Ozpineci	10	5	2	3	3	2.7
R&D	Wide Bandgap Materials	Burak Ozpineci	10	9	4	3	3	3.3
R&D	**Wide Bandgap Materials**							**3.0**

Appendix E – Reviewer and Ratings and Comments and Principal Investigator Responses

FY06 FreedomCAR FCVT APEEM Annual Review
Reviewer Feedback with Presenters' Responses
All Presentations - Grouped by Reviewer

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 8*

Title: **Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**

Presenter: **Leon Tolbert** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Addresses best path to achieving FreedomCAR goals, namely, high-temp inverters.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: All elements relevant and appear achievable. Not sure how necessary to go magnetic free, but worthy to consider and document results. Extra switches may not be best design trade.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good progress on timeline. Most difficult aspects of project lie ahead.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Working 1 kW prototype. Capacitor testing.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**

Presenter: **Leon Tolbert** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: Alternative to magnetics based DC-DC converter but relies heavily on high temperature capacitors. Good complement to SiC switching devices and operation at high frequency.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Modular building block approach is very good and has cost advantage in volume market.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Need to have more content on converter performance of component parameter drift with temperature and component parameter drift with aging. What are the issues of DC life on the capacitors during high temperature operation?

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: This project and the Wide Bandgap efforts at ORNL are synergistic tasks. As part of the Wide Bandgap project, we have evaluated several different devices (diodes, JFETs, and MOSFETs) over a wide temperature range. We have done limited aging testing of devices (SiC JFETs and diodes were tested for several months in a circuit). The results of those efforts are fed directly into this project for design considerations.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Need cycle life validation on the high temperature capacitors being used or proposed. Is there a wear-out mechanism?

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Capacitors selected for the high temperature prototype will be tested and stressed to evaluate their failure mechanisms.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 5***

Title: **Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**

Presenter: **Leon Tolbert** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Significant potential to increase power density and reduce system cost via air cooling.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Good project plan, integrated with industry device developments.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Innovative converter design with fault tolerance thru redundancy, and demonstrated simulation results for hi-temp gate driver.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Developed converter topology.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 5***

Title: **Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**

Presenter: **Leon Tolbert** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: Due to the size and weight of magnetics, it is highly desirable to reduce or eliminate them.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: While eliminating the magnetics is a good goal, if they are merely replaced with capacitors, then I would question the benefit. Should perhaps look at more novel topologies to avoid having to increase the capacitors. Such a technique might include some smaller magnetics, but with more novel circuitry.

Approach sufficiently innovative: No

If no, explain: Should perhaps look at more novel topologies to avoid having to increase the capacitors.

PI's Response to Approach Questions/Comments: The elimination of the magnetics will substantially reduce the weight of the converter. The additional benefits of the proposed circuit topologies are that they will allow the battery to be segregated into multiple strings or modules, with each battery string having a lower overall voltage than the entire string. This should make cell balancing easier than in existing HEVs which has a long string of batteries. In addition, if an individual battery cell fails, then only one module has to be replaced and not the entire string.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: The challenges to high temperature capacitors seem to diminish any positive accomplishments.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Need to be able to solve the capacitor problem.

PI's Response to Technical Accomplishments Questions/Comments: We also have concerns as to the availability and cost of high temperature capacitors. The proposed circuit topologies are not limited to high temperature (air cooling) applications, and if capacitor cost and availability are lacking; this topology can be used with the 105°C cooling loop where capacitor availability is not as problematic as for 150 to 200°C.

Strengths: Elimination of magnetics.

Weaknesses: Addition of more capacitors

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 5***

Title: **Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**

Presenter: **Leon Tolbert** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Which is cheaper and smaller, high temp caps or a transformer. Can a cost target be established for this trade off? What is the estimated cost of the cooling loop you are replacing? Packaging of caps and power devices needs to be demonstrated? What is the efficiency at low power levels 0 - 20 watts?

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

We have concerns as to the availability and cost of high temperature capacitors. The proposed circuit topologies are not limited to high temperature applications, and if capacitor cost and availability are lacking; this topology can be used with the 105ºC cooling loop.

Finding capacitors with sufficient capacitance that can work with 105ºC cooling will be easier than capacitors that work with air cooling where the ambient may be 150 to 200ºC.

During the second and third year of this project, we will be evaluating the packaging of the capacitors and switches into a high temperature module. An estimate of the weight savings and cost savings of eliminating a cooling loop which costs ~$200 will also be determined in the next year.

The converter will not be run at low power levels (such as 0-20 Watts) in a practical application because the efficiency of this converter (and all power electronic converters) is very poor at such low power levels. The housekeeping power supplies for control and gate drives are a fixed loss that will cause efficiency to fall off (less than 50% at such low power levels.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Needs to be built and tested?

Accomplishments Sufficient:

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Can a FMEA be performed on this system - or in general, and of the "system" approaches presented today?

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: An FMEA (Failure Mode and Effects Analysis) can be done on this system. FMEA is usually done by manufacturers for a product. We are developing technology and not a product. We do not anticipate performing an FMEA on this technology. This involves a software tool that we are not familiar with and have not budgeted for in this effort.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**

Presenter: **Leon Tolbert** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Power electronics that can meet the cost and temperature tolerance goals of the FreedomCAR program are critical to the success of the program and for OEMs to be able to offer HEVs that are affordable and can meet customer needs.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Unusual approach that tends to shift the burden from the power electronics to the battery. This is fine assuming that there is no related degradation in battery function or life. Work on gate drives and high temperature capacitors are worthwhile and relevant to the program.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: We do not anticipate that the multilevel dc-dc converter will cause additional burden on the battery in and of itself. Battery burden is mostly a function of state of charge control and the ripple in the current. What it allows is for the battery to be discharged more deeply than in conventional HEVs if the OEM desires. After we have built and tested a full-scale prototype, we will be in a better position to comment on battery effects. The multilevel dc-dc converter concepts will allow the battery to be segregated into multiple strings or modules, with each battery string having a lower overall voltage than the entire string. This should make cell balancing easier than in existing HEVs which has a long string of batteries. In addition, if an individual battery cell fails, then only one module has to be replaced and not the entire string.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good research in several areas as mentioned above.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses: Multiple DC/DC converters seem complex and costly. Need to consider added risks to battery as a result of design approach. Need to take a total vehicle systems approach to the technology. Should not limit analysis to a single component and shift burden of cost/reliability/temperature to other components.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: The multiple dc/dc converters, if built as identical modules should not be costly. From a system perspective the design will accomplish the elimination of a cooling loop by using high temperature components. This will result in considerable cost benefits. We agree that battery affects are important and we will evaluate battery stresses during the next year of the project.

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**

Presenter: **Leon Tolbert** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Battery replacement cost must be considered.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: The multilevel dc-dc converter concepts will allow the battery to be segregated into multiple strings or modules, with each battery string having a lower overall voltage than the entire string. This should make cell balancing easier than in existing HEVs which has a long string of batteries. In addition, if an individual battery cell fails, then only one module has to be replaced and not the entire string Replacement cost of the battery will be much cheaper because only the module that has failed has to be replaced as opposed to an entire battery pack.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 7*

Title: **Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**

Presenter: **Leon Tolbert** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: High temp gate work is needed.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Battery is sufficiently high cost that it has to be robust and durable for 10 years and 150K miles. Too much complexity to protect the option to replace sections of the traction battery.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 8*

Title: **Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**

Presenter: **Leon Tolbert** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 10*

Title: **Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**

Presenter: **Leon Tolbert** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: 1. Questionable high temp operation. 2. Sw. Cap approach is good for low power, very questionable for high power due to associated component losses in high current switching.

Potential to Meet Technical Target: No

If no, explain: SiC device can work in high temperature, but losses dramatically increase. That has very little chance for SiC device to survive unless it's substantially derated.

PI's Response to Relevance Questions/Comments: We also have concerns as to the availability and cost of high temperature capacitors. The proposed circuit topologies are not limited to high temperature applications, and if capacitor cost and availability are lacking; this topology can be used with the 105°C cooling loop and more conventional capacitor technology.

SiC JFETs and MOSFETs on-state losses will double when operated at 200°C as compared to 100°C. However, the switching losses are almost invariant with temperature. Therefore, the total losses will increase by approximately 50% when operated at the higher temperature. All power electronic devices (Si, SiC, GaN) have to be derated if operated at higher than room temperatures. The complete converter design will take into account necessary derating for higher temperature operation.

Approach Rating (1-4): **3**

Approach Justification: Different topologies and component level designs were done. Not practical in many sense, but was considered "exploratory."

Approach sufficiently innovative: No

If no, explain: Target high temperature without practical considerations on (1) loss dissipation in a small area, (2) loss increase at high temperatures on SiC components.

PI's Response to Approach Questions/Comments: High temperature packaging, which includes the ability to extract heat from the power electronic devices, will be addressed during years 2 and 3 of this project.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: A magnetic-less hardware is demonstrated by a subcontractor. Key power stage design, control, high-temp gate drive are all on paper design stage and are far away from practical accomplishment.

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments: Goal is obviously not practical, but perhaps provides answers to auto manufacturers why SiC and high temperature power electronics are not practical at least for the next 5 to 10 years.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: This is a challenging project that incorporates new circuit designs, high temperature packaging, high temperature gate drives, and high temperature capacitors. Automakers have a desire to move away from a separate cooling loop and cool power electronics by air-cooling, which is what this project addresses. The targeted circuit topology is still applicable for lower temperature operation if some technologies (such as high temperature capacitors and high temperature packaging are not yet commercially available.)

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 9***

Title: **Advanced Converter Systems for High Temperature (Air Cooling) HEV Environments**

Presenter: **Leon Tolbert** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification: Combines advantages of new converter design with the use of high temp devices to gain advantages in peak power to weight and peak power to volume well in excess of FreedomCAR goals at a reasonable estimated cost.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Addresses both elimination of magnetics and the development of high temp packaging and gate drive to achieve high goals. Risk is in the availability and quality/reliability of all the high temperature components (diodes, JFETS, caps, etc.). Needs to focus considerable effort on packaging and reliability as this could be the showstopper.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Excellent progress on converter & gate drive design with simulation and prototyping. Would be nice to be farther along in packaging and cap assessment.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Gate driver design & simulation

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Ambitious combination of high temperature packaging & magnetic-force design.

Weaknesses: Reliance on the commercial industry for availability & development of needed devices.

Recommendations for Additions/Deletions to Project Scope: Need significant emphasis on reliable high temperature packaging.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Advanced Thermal Interface Materials to Reduce Thermal Resistance**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: The CNT work is very relevant but concern is cost of growing on DBC.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: We plan on doing a preliminary cost analysis. We are also looking at other novel materials such as metal coated particles based polymeric compounds.

Approach Rating (1-4): **3**

Approach Justification: Having 3 approaches to grow carbon nanotubes (CNTs) on metal substrate is very valid. When will downselect occur?

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: In FY07, we will concentrate on one approach that yields the best growth of nanotubes. As mentioned previously, we are looking at other novel interface materials also.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Noteworthy accomplishments to date, but need to broaden scope. For example, compare CNT to Semikron's more recent thermal grease. What is the degradation of CNT when thermal cycled vs. thermal grease? In conjunction with thermal grease?

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: We plan to compare the performance of these novel TIMs with other interface materials in the market. The point about degradation of CNTs is important. We are acquiring in-house a test stand that will enable us to make thermal resistance measurements. We plan to investigate the impact of thermal cycling on the performance of these TIMs.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Add some content on path to commercialization of CNT-coated DBC.

Additional Comments: CNTs growth rates are very consistent so forming a more-or-less uniform "brush-like" layer should work out.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: We will look at the system level impact of these TIMs (both CNTs as well as metal coated particle based polymeric compounds).
At this stage, we are characterizing the thermal performance of these TIMs in a simple test setup. The next stage would be to characterize their performance in an IGBT package.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 6***

Title: **Advanced Thermal Interface Materials to Reduce Thermal Resistance**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **2**

Relevance Justification: Though the idea has potential to improve RTim, it doesn't seem like the impact on overall system cost would be very large.

Potential to Meet Technical Target: No

If no, explain: See justification above.

PI's Response to Relevance Questions/Comments: If it improves RTIM, it will increase the heat flux that can be dissipated from the die at any given temperature. That is the goal here.

Approach Rating (1-4): **3**

Approach Justification: Would like to have seen a preliminary cost analysis planned earlier in the project.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: We will perform a cost analysis.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry **Reviewer's Ability to Rate (1-10): 1**

Title: **Advanced Thermal Interface Materials to Reduce Thermal Resistance**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification: Good fundamental S&T. Kind of far down into component research. What's the transition strategy?

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments: We are currently exploring the performance of these novel interface materials (based on CNTs and metal coated particles based polymeric compounds). We will investigate the system level implications (cost, complexity and performance) in FY07.

Approach Rating (1-4): **3**

Approach Justification: Although I'm not an expert, approach appears sound. Unclear to me why this approach is best way to achieve objectives, but I would give the experts the benefit of the doubt.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: The idea is to get maximum gain in thermal performance by making minimum number of changes to the existing IGBT structure. We have not incorporated these TIMs in the actual package structure. That would be the next stage. In this first stage, we are attempting to establish the thermal performance of these TIMs.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Progress looks exciting. When will the results not be "very preliminary?"

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: In FY07, we aim to have comprehensive results.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **Advanced Thermal Interface Materials to Reduce Thermal Resistance**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **2**

Relevance Justification: While improving thermal interface materials is important, this work seems to ignore the bigger impact of totally eliminating the thermal barrier.

Potential to Meet Technical Target: No

If no, explain: Other techniques such as direct die bonding (silicon being put directly onto the cold plate) has a big advantage over these incremental improvements.

PI's Response to Relevance Questions/Comments: We do have a project with the reduced thermal resistance IGBT structure where the grease/thermal interface material is eliminated and the liquid jet directly impinges on the backside of the DBC layer.

We have adopted parallel paths via separate projects. This specific project aims to improve the thermal interface materials. The current thermal interface materials used in typical IGBT package have a high thermal resistance and there is scope for considerable improvement.

Certainly, direct die bonding has a big advantage because it eliminates a number of layers. However, it also requires substantial changes in the architecture of the IGBT package.

The specific goal here is to cut down on the thermal resistance of the interface material with minimal changes in the current architecture of the IGBT package.

Approach Rating (1-4): **2**

Approach Justification: As was pointed out in one of the questions, a process that requires soldering the chip to a large heat sink is problematic.

Approach sufficiently innovative: No
If no, explain: Eliminate the barrier instead of just reducing its impact.

PI's Response to Approach Questions/Comments: It is not clear what the reviewer means. We are not proposing to solder the chip to the heat sink.

We do have a project where we are doing this, but it is not yet clear if that approach will be successfully adopted. Reducing the thermal resistance of the interface materials provides an alternative pathway for meeting the program goals. A down select between the parallel alternatives will be made once a full assessment of the thermal performance and the system impacts for the various options has been completed.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Need to get much more improvement in heat removal than what is offered here.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Need to get much more improvement in heat removal than what is offered here.

PI's Response to Technical Accomplishments Questions/Comments: There is a tradeoff involved here. In this specific project, the ultimate goal is to improve heat removal capabilities via minimum changes in the existing IGBT package structure. Our preliminary analysis suggests that 10-20 C improvement in chip temperature could be achieved. These TIMs could also be implemented in conjunction with other cooling technologies.

Strengths:

Weaknesses: Lack of recognition of the superior alternatives and lack of consideration of the manufacturing impacts (soldering) are two weaknesses.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: There are superior alternatives, but they also require significant changes to the current IGBT package structure. Again, we do not propose soldering any layer to the heat sink.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Advanced Thermal Interface Materials to Reduce Thermal Resistance**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **1**

Relevance Justification: While thermal management is important for the FreedomCAR program to meet its goals, it does not appear that this research project will substantially contribute to the knowledge base or assist in meeting the goals.

Potential to Meet Technical Target: No

If no, explain: Unlikely to be able to meet cost goals.

PI's Response to Relevance Questions/Comments: It is not clear why the reviewer says this. This project ultimately aims at improving the heat dissipation capabilities of the IGBT package. Our preliminary analysis suggests that 10-20°C improvement in chip temperature could be achieved. These TIMs could also be implemented in conjunction with other cooling technologies.

We will look into aspects related to cost effectiveness.

Approach Rating (1-4): **2**

Approach Justification: Interesting technical concept; innovative applications of CNT; but probably will have limited technical practicality for automotive applications.

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments: This project is not just about CNTs. We are also exploring polymeric compounds based on metal-coated particles. We have not determined that these solutions will be impractical for the automotive application.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Work done to date is reasonable but does not consider the systems implications when integrated into an automotive system. Will probably present other challenges that make it ultimately impractical and too expensive.

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: The system level implications will be addressed.

Strengths:

Weaknesses: Limited technical practicality. Too complex a solution to a simple and straightforward problem.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: The solution may not be that complex. We will consider the system level implications.

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **Advanced Thermal Interface Materials to Reduce Thermal Resistance**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 2

Relevance Rating (1-4): **2**

Relevance Justification: Cost effectiveness of technology.

Potential to Meet Technical Target: No

If no, explain:

PI's Response to Relevance Questions/Comments: We will look into aspects related to cost effectiveness.

Approach Rating (1-4): **2**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM **Reviewer's Ability to Rate (1-10): 7**

Title: **Advanced Thermal Interface Materials to Reduce Thermal Resistance**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **2**

Relevance Justification: Comparing it to other mechanical methods may lead us to conclude that this approach won't be competitive based on what we've learned to date.

Potential to Meet Technical Target: No

If no, explain: See Relevance Justification above.

PI's Response to Relevance Questions/Comments: It is not clear why the reviewer makes this conclusion. The other important aspect is that while we are exploring carbon nanotubes, we are also looking into metal-coated particle based polymeric compounds. We will work towards laying out the advantages and disadvantages of these novel materials as compared to existing conventional TIMs.

Approach Rating (1-4): **2**

Approach Justification: Cost of fitting to system seems insurmountable. Identify obstacles (cost) and attack.

Approach sufficiently innovative: No
If no, explain:

PI's Response to Approach Questions/Comments: We are planning on assessing the system implications of using these novel TIMs from the viewpoint of cost, performance and system complexity.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 8***

Title: **Advanced Thermal Interface Materials to Reduce Thermal Resistance**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 4

Relevance Rating (1-4): **1**

Relevance Justification:

Potential to Meet Technical Target: No

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification:

Approach sufficiently innovative: No
If no, explain: Doesn't seem to have a clear understanding of what can and cannot be done in the inverter.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 10***

Title: **Advanced Thermal Interface Materials to Reduce Thermal Resistance**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 3

Relevance Rating (1-4): **1**

Relevance Justification: Thermal interface materials are a significant concern in improving passive cooling of IGBT devices, however, it is extremely unlikely that fundamental research into carbon nanotubes, while fashionable, will lead to a commercially available interface material at a sufficiently reasonable cost for incorporation by OEMs in any reasonable amount of time. Metal coated polymers are more likely to lead to a usable product.

Potential to Meet Technical Target: No

If no, explain: Carbon nanotubes technology is much too early in its development to meet reliability or cost goals of FreedomCAR in the given timeframe.

PI's Response to Relevance Questions/Comments: We are not solely focused on carbon nanotubes. We are looking at metal-coated particle based TIMs.

It is not clear that this has been established. We will look at the system implications of these novel TIMs in terms of cost, system complexity and performance.

Approach Rating (1-4): **2**

Approach Justification: Shift focus from carbon nanotubes to metal coated polymers or find commercial supplier for carbon nanotubes.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: We are investigating polymer compounds based on metal-coated particles.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Seems like the C nanotube growth is being driven by Colorado, Boulder; not clear what NRELs contribution to this effort is. Why is the C nanotube vs. Cu analysis done without grease? Everyone would use with grease. Is this the only result? No data on embedded metal-coated particles.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: More comprehensive experiments are currently being performed. The results presented at the review were very preliminary.
At NREL, we are acquiring a test stand to perform thermal resistance measurements. This test stand will help in characterizing the thermal performance of these novel TIMs (CNTs as well as metal-coated particles based polymers) that our subcontract partners are developing. We plan to characterize the thermal performance over a wide temperature and pressure range, as well as characterize the impact of thermal cycling on the performance.

Strengths: Thermal interface materials should be studied. They do affect the passive cooling significantly.

Weaknesses: Carbon nanotube research is misplaced here. The chances of developing a cost effective, reliable system for FreedomCAR are very limited. Need more characterization of what has been fabricated.

Recommendations for Additions/Deletions to Project Scope: Need more characterization of what has been fabricated.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: We will investigate the system level implication of using these TIMs (both CNTs as well as metal coated particle based polymer compounds).

Comment is not very clear, but we will be conducting comprehensive experiments.

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 2***

Title: **Advanced Thermal Interface Materials to Reduce Thermal Resistance**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification: It seems that this work is too far out to be really applicable to the FreedomCAR. The topic is very important, but the focus on CNT seems to have far too many uncertainties.

Potential to Meet Technical Target: No

If no, explain: There are other technologies, such as composite materials and/or alloys that will help reach targets sooner and more reliably.

PI's Response to Relevance Questions/Comments: Actually, we are not restricting ourselves to CNTs. We are exploring metal coated particle based polymeric compounds as well.
We will explore other alternatives also.

Approach Rating (1-4): **2**

Approach Justification: I believe the focus should be shifted from CNT to alloys or other more realistic materials.

Approach sufficiently innovative: No
If no, explain: I believe many folks are working in this area. It is unclear how this project enhances the state of the art…especially for the time frame of the FreedomCAR Program.

PI's Response to Approach Questions/Comments: As mentioned previously, we are not focusing solely on CNTs.

There are several groups working on CNTs. Our focus is to explore the application of CNTs in the automotive context.
Regarding metal-coated particles based polymeric compounds, we have established a subcontract with Federal Technology Group (FTG). They have a very strong base in the metal-coated particle technology. FTG is also working in conjunction with companies such as GE and Honeywell to develop this novel TIM based on metal-coated particle technology.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Given the limitations noted above, some good work has been done. Some obvious tests were missed, such as adding grease to the comparison w/unadorned copper. This should not have required much time or money.

Accomplishments Sufficient: Yes-marginally

Significant Accomplishments During Year: Performed initial evaluation and testing. Bid equipment for next stage.

PI's Response to Technical Accomplishments Questions/Comments: In FY07, we will have comprehensive results paying attention to the details pointed out by the reviewer.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments: I just don't think that $300K/yr is justified for this work.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 9*

Title: **Advanced Traction Motor Development**

Presenter: **Josh Ley** ***Laboratory/Company:*** **UQM**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: This type of work is absolutely essential to the Freedom Car project.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Appears to use an innovative, yet practical approach to achieving high performance at a reasonable cost.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: If the design is prototyped and tested it could take this rating to a "4."

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Verification of higher peak capability due to simply meeting the continuous rating with high coolant temperature.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Practicality

Weaknesses: Did not seem to sufficiently optimize tradeoffs of the higher reluctance designs.

Recommendations for Additions/Deletions to Project Scope: Build and test a prototype.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry **Reviewer's Ability to Rate (1-10): 10**

Title: **Advanced Traction Motor Development**

Presenter: **Josh Ley** ***Laboratory/Company:*** **UQM**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: Project moves technology in the right direction but is not a real technical leap. Relevant in that speeds are higher (10K vs 6K), magnet temp's are higher (180°C vs 170°C) and higher stator currents (400 A vs 250 A. Basis is Prius.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: I'd like to see more stretch in the concepts. Recent Prius AC machines are already at 19.9K rpm, 650 V, 170°C (or more?), w/o needing higher PM content.

Approach sufficiently innovative: No
If no, explain: I'd like to see comparison of torque/kg PM vs Prius and stator upper copper density vs Prius.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Solid progress and well thought out objectives. Focus is on technical challenges.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Machine concept downselected from 3 contenders. UQM is company with solid expertise in novel PM machine design.

Weaknesses: May not be pushing the envelope enough.

Recommendations for Additions/Deletions to Project Scope: How would other material choices benefit the design. Have in mind the Hoganas Co. 3D type stator material.

Additional Comments: The comment of realizing \$2/kw for the full-up machine seems overly optimistic in an era of escalating material costs. Cu ↑, Fe ↑, Pm's ↑, and no indication prices will fall in 2010 time frame. Need to address in cost summary.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 7*

Title: **Advanced Traction Motor Development**

Presenter: **Josh Ley** ***Laboratory/Company:*** **UQM**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: PI must consider NVH aspects in the design of motor for automotive applications.

Potential to Meet Technical Target: Yes

If no, explain: Partially.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM **Reviewer's Ability to Rate (1-10): 5**

Title: **Advanced Traction Motor Development**

Presenter: **Josh Ley** ***Laboratory/Company:*** **UQM**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: Research is very relevant to the mission of the FreedomCAR program and the needs of the OEMs for lower cost, compact, lightweight motors.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Technical approach is good. Experience of the PI in the supply base and in industry brings a businesslike approach to the research project. PI appears to have a good understanding of the technology and its relevance to the auto industry.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Would like to see more background cost details to substantiate the cost accomplishments reported. Would like to see more detailed data on the technical accomplishments reported. Has the PI adequately addressed NVH?

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Good grounding in industry brings a practical approach to the research being conducted.

Weaknesses: Need to see more detailed data to fully appreciate technical accomplishments and costs being reported.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 6***

Title: **Advanced Traction Motor Development**

Presenter: **Josh Ley** ***Laboratory/Company:*** **UQM**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Good quick study. Similar analysis of power electronics needed?

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: What are the motor design implications on the power electronics. Does the low cost motor have cost implications on the power electronics? Should there be a facing Phase 1 analysis on power electronics?

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: More work on bonded magnets cost reduction opportunities would be beneficial.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Power Electronics Implications and costs.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 6***

Title: **Advanced Traction Motor Development**

Presenter: **Josh Ley** ***Laboratory/Company:*** **UQM**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Good analysis work. Very useful.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Would like to see more areas covered such as noise, magnet, structure. Unsure about cost analysis, does not really make sense. No NVH.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year: Good start but unsure of completeness.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 9***

Title: **Advanced Traction Motor Development**

Presenter: **Josh Ley** ***Laboratory/Company:*** **UQM**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Design optimization to lower magnet cost and to achieve efficiency goal size and weight are also reduced.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Conservative approach but practical by taking existing design with farther optimization.

Approach sufficiently innovative: No
If no, explain: It's conventional, but would have chance to meet DOE target.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Cost target, size and weight are all met with detailed bill of materials priced out.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Cumulative hardware design experience to improve and optimize the existing design further. Have resources to perform the work.

Weaknesses: Not obvious except wider constant power range is not addressed.

Recommendations for Additions/Deletions to Project Scope: Address a wider constant power speed ratio in the system level design.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D **Reviewer's Ability to Rate (1-10): 2**

Title: **Advanced Traction Motor Development**

Presenter: **Josh Ley** ***Laboratory/Company:*** **UQM**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Improved traction motor exceeds targets for power density, torque density and specific power providing a good chance of meeting FreedomCAR goals.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Innovative motor design cuts significantly the cost and weight of magnets improving specific power and power density.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good simulation of torque, power and efficiency for the new motor.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Air Cooling for Power Electronics**

Presenter: **Desikan Bharathan** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: "Air is the ultimate heat sink." This is exactly the point.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Need to validate the assumed heat transfer coefficients used. The concept of air jets would appear feasible but should be compared to other methods.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: Agreed – we will attempt to maintain a broad view with respect to other air cooling technologies.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Appears to be relatively early in the project stage. Lots of literature research and commercial analysis is complete.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Will the proposed air jet approach require de-humidified air?

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: We are still in the phase of proving the concept of using air and what will be the "best" approach. There are a number of alternatives under consideration, and we may require de-humidification. That requirement will be evaluated as part of the thermal systems.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 8***

Title: **Air Cooling for Power Electronics**

Presenter: **Desikan Bharathan** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 2***

Title: **Air Cooling for Power Electronics**

Presenter: **Desikan Bharathan** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Air cooling high temp power electronics is perhaps the most disruptive breakthrough I can think of for the FreedomCAR Program.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Approach appears to be more like a study than a technology development. This is good and bad. Good: not flagging a "miracle solution." Bad: not clearly leading to any breakthroughs.

Approach sufficiently innovative: Maybe, but I'm not an expert
If no, explain:

PI's Response to Approach Questions/Comments: Our first step was to identify candidate technologies to meet the performance goals. Next we will be experimentally evaluating and developing the thermal performance of the top candidate technologies. We will also evaluate the technologies that meet the performance goals in terms of system integration issues. Experimental validation and developing the necessary thermal sub-systems will be key areas of focus for this project in FY07.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Mostly a systems study and brochure review. The results to date are interesting, encouraging, but no breakthrough. Speaker himself questioned feasibility of his "goals." Experimental verification of goals would be a breakthrough.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Identified aggressive goals.

PI's Response to Technical Accomplishments Questions/Comments: - See comments above.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **Air Cooling for Power Electronics**

Presenter: **Desikan Bharathan** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **2**

Relevance Justification: While the ultimate cooling media is air, that does not mean that it is the right way to get the heat out of a specific component.

Potential to Meet Technical Target: No

If no, explain: Liquid (or two phase) cooling of electronics is likely to prevail.

PI's Response to Relevance Questions/Comments: We are pursuing a number of cooling technology options – single phase jet/spray, two phase jets/sprays, and coolant alternatives. In FY07, we plan to present additional details on the tradeoffs between these various approaches.

Approach Rating (1-4): **3**

Approach Justification: The use of existing reference points (hot wire anemometer and turbine blades) is a good starting point.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Improvements are still fairly nominal.

Accomplishments Sufficient: No

Significant Accomplishments During Year: No breakthroughs were achieved.

PI's Response to Technical Accomplishments Questions/Comments: We are fairly early in the development cycle with this project – hopefully more significant breakthroughs will be achieved in the coming year(s).

Strengths:

Weaknesses: Very high velocities, potentially creating audible noise, along with material erosion are problems not addressed.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Experimental validation and evaluations that address the issues above along with developing the necessary thermal sub-systems will be key areas of focus for this project in FY07.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **Air Cooling for Power Electronics**

Presenter: **Desikan Bharathan** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: This is the ultimate solution for cooling the power electronics and motor. It's worth a look.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: If you need more surface area on a die you may want to look at the latest solar cell die. A lot of patterning is done to keep photons bouncing around on the die. May be difficult to adapt this technology to a power die but…

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: We will look into this.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good start on modeling, but measured data is needed.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Experimental data will be a key focus point in FY07.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Air Cooling for Power Electronics**

Presenter: **Desikan Bharathan** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **1**

Relevance Justification: While thermal management is important for the FreedomCAR program to meet its goals, it does not appear that this research project will substantially contribute to the knowledge base or assist in meeting the goals. Air cooling is unlikely to be practical for conventional Si materials.

Potential to Meet Technical Target: No

If no, explain: See justification above.

PI's Response to Relevance Questions/Comments: We believe that there may be an approach for which air cooling will prove practical, especially with SiC technology. Even with SiC technology, the air cooling approach will likely need to be enhanced from current methods – esp to meet the volume reduction targets, and the related heat flux requirements.

Approach Rating (1-4): **1**

Approach Justification: Research presented assumes a 30°C ambient air temperature which is unlikely to be found in an auto underhood environment. PI should evaluate air cooling when ambient air temperatures are over 100-120°F.

Total systems integration may negate the advantages of the proposal.

Research should be long range, high risk, stretch research to justify federal funding. This research does not seem to meet these requirements.

Approach sufficiently innovative: No

If no, explain:

PI's Response to Approach Questions/Comments: There are a number of alternative approaches for air cooling that we are assessing. Most likely, the air cooling approach will likely require directing air from outside the engine compartment – that is where the assumption of 30º C air comes from. This approach seems feasible, as the Toyota Prius currently uses cabin air to cool the battery pack. Our preliminary analysis shows that using 120ºF air to cool the inverter (even with SiC technology) will be very challenging.

Experimental validation and developing the necessary thermal sub-systems will be key areas of focus for this project in FY07.

Technical Accomplishment and Progress Rating (1-4): **1**

Technical Accomplishment and Progress Justification: Research presented assumes a 30°C ambient air temperature which is unlikely to be found in an auto underhood environment. PI should evaluate air cooling when ambient air temperatures are over 100-120°F.

Total systems integration may negate the advantages of the proposal.

Accomplishments Sufficient: No

Significant Accomplishments During Year: See justification above.

PI's Response to Technical Accomplishments Questions/Comments: - Same as above.

Strengths:

Weaknesses: PI suggests that this approach may be beneficial when SiC technologies become available, but if SiC meets its expectation, the temperature characteristics would not require sophisticated air cooling.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Even with SiC technology, the air cooling approach will likely need to be enhanced from current methods – esp to meet the volume reduction targets, and the related heat flux requirements.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Air Cooling for Power Electronics**

Presenter: **Desikan Bharathan** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 1

Relevance Rating (1-4): **1**

Relevance Justification: This project must be worked on in the context of silicon carbide.

Potential to Meet Technical Target: No

If no, explain:

PI's Response to Relevance Questions/Comments: Our focus has been on assessing air cooling technologies with the potential to dissipate up to 200 W/cm2 of heat – this is somewhat independent of the chip material technology – except that the maximum temperature requirement is higher. The application to SiC technology will continue to be a priority and we will express the thermal performance results in terms of SiC technology.

Approach Rating (1-4): **1**

Approach Justification: May not be an appropriate application.

Approach sufficiently innovative: No
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 7***

Title: **Air Cooling for Power Electronics**

Presenter: **Desikan Bharathan** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: Total systems implications need to be identified and quantified (onboard compressor seems too costly).

Approach sufficiently innovative: No
If no, explain: See justification above.

PI's Response to Approach Questions/Comments: Experimental validation and developing the necessary thermal sub-systems will be key areas of focus for this project in FY07.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Look forward to systems design challenges.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 8***

Title: **Air Cooling for Power Electronics**

Presenter: **Desikan Bharathan** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 4

Relevance Rating (1-4): **1**

Relevance Justification:

Potential to Meet Technical Target: No

If no, explain: If this looked at SiC inverters and if it would be possible to have air cooling it may be a useful project.

PI's Response to Relevance Questions/Comments: Our focus has been on assessing air cooling technologies with the potential to dissipate up to 200 W/cm2 of heat – this is somewhat independent of the chip material technology – except that the maximum temperature requirement is higher. The application to SiC technology will continue to be a priority and we will express the thermal performance results in terms of SiC technology.

Approach Rating (1-4): **1**

Approach Justification:

Approach sufficiently innovative: No
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No
Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 9*

Title: **Air Cooling for Power Electronics**

Presenter: **Desikan Bharathan** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification: Air cooling is a low cost, preferred method for cooling consumer and automotive electronics. Improving airflow for improved cooling offers much improvement at low cost. Not clear from presentation however, what the R&D improvement goals are and how closely they meet FreedomCAR goals.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: The goal of this project in FY06 was to assess the potential for reducing the cost and complexity of the cooling system for power electronics using air. This assessment was done in the context of meeting the overall thermal control requirements of dissipating up 200 W/cm2 of heat while maintaining the required chip operating temperatures (200°C for SiC). There was some material presented near the end of the presentation that showed the potential for air to meet these requirements, as well as the infeasibility of the refrigerated air approach was discussed. We will attempt to do a better job of highlighting the performance characteristics to the overall project objectives.

Approach Rating (1-4): **3**

Approach Justification: Microjet coolers have potential for significant increased air cooling performance. How would they be integrated into power electronics modules and systems? Integration issues should be addressed.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: Our first step was to identify candidate technologies to meet the performance goals. Next we will be experimentally evaluating and developing the thermal performance of the top candidate technologies. We will also evaluate the technologies that meet the performance goals in terms of system integration issues.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good progress of CFD analysis of airflow in the microjet devices and on analysis of improved cooling. Need to discuss integration.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Experimental validation and system integration issues will be key areas of focus for this project in FY07.

Strengths: Microjet coolers promise low cost, high reliability cooling improvement.

Weaknesses: Need to discuss integration of device into power electronic modules and systems.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 8***

Title: **Air Cooling for Power Electronics**

Presenter: **Desikan Bharathan** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Really need experimental results. Include comparison including compressor. Can this really reach sufficient levels of cooling?

Potential to Meet Technical Target: No

If no, explain: I really question whether this can meet requirements of power density; total system may require a lot of volume for all the components.

PI's Response to Relevance Questions/Comments: Experimental data will be a key focus point in FY07.

We will be doing an thermal sub-system evaluation of this technology in FY07.

Approach Rating (1-4): **3**

Approach Justification: Overall, the approach is good and appropriate. I believe that the most innovative technologies have been identified. I think some system level issues have been glossed over.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: We will be doing an thermal sub-system evaluation of this technology in FY07.

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Identified & simulated very high performance air cooling system. Began looking at system.

Accomplishments Sufficient: Yes
Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Experiments! Acoustics. Total system volume.

Additional Comments: More lively presentation, please!

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Experimental data will be a key focus point in FY07.

We'll try to improve the presentation – especially with the exciting results coming in FY07.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 8***

Title: **Benchmarking of Competitive Technologies/Component Characterization**

Presenter: **Bob Staunton/Larry Seiber** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: It is important to understand the competition and other technology choices.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Testing and side-by side comparisons are good choices, but could be supplemented by some design analysis.

Approach sufficiently innovative: No
If no, explain: More than just testing should be pursued. Add analysis.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: The work done to date is good - from an empirical standpoint.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Valid testing with technical challenges.

Weaknesses: Need to supplement the test results with some analysis of the designs, rather than just treating the inverter and motor as black boxes.

Recommendations for Additions/Deletions to Project Scope: Add analysis.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: ORNL does not treat the inverter and motor as black boxes. First, the subassemblies were assessed to obtain detailed design and packaging data. Next, ORNL researchers have taken both design and performance data and used it in motor models such as Motorsoft SPEEDCAD, Flux2D (FEA), and PSAT (ORNL/Sentech). Other researchers at ORNL have used the data to (1) perform fabrication and cost analyses for the Prius motor and (2) conduct thermal control studies using ORNL's HEATING 7.3 , a general-purpose, finite-difference conduction heat transfer model. Much of this work was funded by other projects and documented in their technical reports. Presently ongoing within the Benchmarking project is an effort to improve the accuracy of another motor model using data obtained from no-load and back-emf tests. The model will effectively incorporate effects of saturation and the impact of variance in other parameters such as stator resistance and inductance, all of which fluctuate with speed, current, or temperature. The efforts to improve the motor model will aid in understanding the operational behavior of the 2006 Accord motor and other interior permanent magnet motors of similar design.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 10***

Title: **Benchmarking of Competitive Technologies/Component Characterization**

Presenter: **Bob Staunton/Larry Seiber** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Benchmarking is proving to be invaluable but the test conditions are crucial to what the results are.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: AC-drives - the test conditions may be problematic. Magnets, very good. Capacitors, very good.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Adequate summary but more detail on test setup necessary. For example, why was the Prius capacitor unstable below 3 kHz?

Accomplishments Sufficient: No

Significant Accomplishments During Year: Too much detail missing and need conclusions.

PI's Response to Technical Accomplishments Questions/Comments: The Prius capacitor module was unstable below 3 kHz, not the capacitor itself. The DAQ software monitors the dielectric temperature for stability in order to determine ESR. This measurement has a narrow window of acceptance. The configuration of the capacitor module consists of bus bars and a potting material that could have contributed to the ESR drifting at the lower frequencies.

Strengths: PIs have excellent experience to carry out.

Weaknesses: Need to see conclusions and directional trends.

Recommendations for Additions/Deletions to Project Scope: AC drives - what is real test setup? Very difficult to trust AC powermeter measurements of inverter to machine power flows, power factor, desp. factor, etc. Capacitors and magnets - DC life test, aging effects.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: The test setups are described in our technical reports for the Prius and Accord. As discussed in the Prius report (Sect. 3.3.2), numerous special tests were conducted to verify the accuracy of the data obtained from the Yokogawa power analyzer. These tests were deemed necessary after obtaining higher-than-expected efficiencies in the inverter. The tests confirmed that the power analyzer was consistently producing accurate data (estimated to be within 1%).

It is true that producing power calculations in a high-EMI environment using a noisy current signal is not ideal; however, even if one were to attempt the most fundamental power calculations using voltage and current waveforms, the results would not be necessarily more defendable for the same reason (noise on the current signal).

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 7*

Title: **Benchmarking of Competitive Technologies/Component Characterization**

Presenter: **Bob Staunton/Larry Seiber** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Since this work documents what is already in production, it doesn't push the envelope or provide new solutions in itself. However, it is foundational to documenting the state-of-the-art and helps us not to "reinvent the wheel." It is also essential to establish a reference point upon which we can gage our progress.

Potential to Meet Technical Target: No

If no, explain: Not by itself (see above).

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Would like to have seen more in-depth analysis of control schemes used by Honda and Toyota.

Approach sufficiently innovative: No
If no, explain:

PI's Response to Approach Questions/Comments: This project is designed to evaluate the design, packaging, and performance potential of the PMSM/inverter systems. While it is recognized that knowledge of the specific algorithms of the Honda and Toyota control schemes would be extremely useful the ECU code used in these vehicles cannot be determined experimentally. It was decided that the effort to analyze control schemes would be outside the scope of this project. It is believed that motor/inverter control methods developed by ORNL are similar to those used by Honda and Toyota, especially for steady-state conditions.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Nice job overcoming difficulties in testing someone else's system. Would like to have seen more collaboration with suppliers (electric machine and inverter).

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Established baseline for comparing future developments in systems and components.

PI's Response to Technical Accomplishments Questions/Comments: Accomplishing the goals of this project within our resources does not enable us to engage in extensive collaboration with suppliers although we invite comments, direction, or expressions of technical needs repeatedly during the year during status reviews. We have often responded to requests for specific data by performing additional work as is evident in the FreedomCAR annual progress report that will be issued in the next few months. Also, although the testing of PMSMs and inverters presents significant technical challenges, ORNL is pursuing a fairly methodical approach to each new system that does not depend on collaboration with suppliers.

Strengths:

Weaknesses: Could have been more detailed in the area of control methods! (a) What do Honda and Toyota use, and (b) What methods did ORNL use in dyne tests.

Recommendations for Additions/Deletions to Project Scope: See Weaknesses.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: During the presentation, there was not sufficient time to adequately address this complex topic. This topic is best left to the technical reporting process. Reports on both the Prius and Accord have been issued this year and each describes the inverter-motor controller used in our laboratory. The Prius report addresses this in greater detail. As for the Honda and Toyota controllers, this project is designed to evaluate the design, packaging, and performance potential of the PMSM/inverter systems. The Honda and Toyota control schemes are outside the scope of this project (see previous comment). Detailed reporting on the ORNL methods used during the dyne tests will also be reported on in the upcoming Annual Report.

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 7*

Title: **Benchmarking of Competitive Technologies/Component Characterization**

Presenter: **Bob Staunton/Larry Seiber** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Needs consistent benchmarking data collection methodology.

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient:

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 7***

Title: **Benchmarking of Competitive Technologies/Component Characterization**

Presenter: **Bob Staunton/Larry Seiber** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Benchmarking is critical for DOE and the OEMs to understand the pace of technology development; to identify new design approaches and to evaluate cost, reliability, & durability.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Only shortcoming may be the need for more discipline in the gathering and reporting of data. Not enough information was presented to be able to confirm or deny a feeling that more rigor is needed in the overall process of gathering data.

Approach sufficiently innovative: No

If no, explain: This is not a problem. Benchmarking need not be innovative; just needs to be consistent, repeatable, and well documented.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Breadth of benchmarking and thorough analysis

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Might consider closer collaboration with ANL regarding benchmarking to ensure that both labs are following common, straight forward, consistent, rigorous procedures that are repeatable and reproducible regardless of the facility at which the benchmarking is conducted.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Following common and consistent procedures at ORNL and ANL for the two testing programs is precluded for the same reasons that both ORNL and ANL are performing benchmark testing of frequently the same vehicle systems: they are fundamentally different programs with different goals. To date, the ANL testing has been of in-vehicle systems as operated by the integrated vehicle control system (ECU). Also, ANL tests the entire vehicle including the engine and exhaust gases, etc. Their mission is to evaluate the fuel efficiency and levels of emissions of the vehicle. At ORNL, our goal is to evaluate the design, packaging, and performance potential of the PMSM/inverter systems. This does not require us to attempt to duplicate the control scheme of the vehicle or to provide cooling similar to that provided in the vehicle. As an extreme example, in Prius motor/inverter testing, our Opal-RT software operated the system, field weakening was manually adjusted, and the motor was cooled at 0 C for low-speed, high-torque conditions. The ORNL test configuration provides greater control over the motor/inverter system and produces data which cannot be obtained with the ANL configuration and ECU control. How a lab approaches chassis dyne testing of an entire vehicle must differ in many ways from the testing of selected subsystems in a controlled test cell. This is especially true since ANL testing of the motor/inverter is largely controlled by highly integrated vehicle systems.

Reviewer Affiliation: OEM **Reviewer's Ability to Rate (1-10): 6**

Title: **Benchmarking of Competitive Technologies/Component Characterization**

Presenter: **Bob Staunton/Larry Seiber** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Keeping a good pulse on state of industry using objective measures.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Need to standardize process and metrics! Quantify performance in consistent units and compare/confirm to Vehicle/systems and component work being done at all labs (ANL, ORNL, INL…….)

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: A system-to-system data comparison between ORNL and ANL testing is precluded for the same reason that both ORNL and ANL are performing benchmark testing of frequently the same vehicle systems: they are fundamentally different programs with different goals. To date, the ANL testing has been of in-vehicle systems as operated by the integrated vehicle control system (ECU). Also, ANL tests the entire vehicle including the engine and exhaust gases, etc. Their mission is to evaluate the fuel efficiency and levels of emissions of the vehicle. At ORNL, our goal is to evaluate the design, packaging, and performance potential of the PMSM/inverter systems. This does not require us to attempt to duplicate the control scheme of the vehicle or to provide cooling similar to that provided in the vehicle. As an extreme example, in Prius motor/inverter testing, our Opal-RT software operated the system, field weakening was manually adjusted, and the motor was cooled at 0°C for low-speed, high-torque conditions. The ORNL test configuration provides greater control over the motor/inverter system and produces data which cannot be obtained with the ANL configuration and ECU control.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Investigate investments needed to have capability to test throughout the full operating range.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): Reviewer did not provide number.***

Title: **Benchmarking of Competitive Technologies/Component Characterization**

Presenter: **Bob Staunton/Larry Seiber** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): Reviewer did not provide number.

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: No

If no, explain: This though provides the necessary information to benchmark and guide research work.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: No

If no, explain: This is basic knowledge work that is extremely important. Needs consistency in benchmarking.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 8***

Title: **Benchmarking of Competitive Technologies/Component Characterization**

Presenter: **Bob Staunton/Larry Seiber** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification: Benchmarking Prius, Honda, etc. is an essential part of the program in setting reasonable goals for FreedomCAR and motivating improvements. Also may provide ideas for improved design.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Good approach industry benchmarking at all levels from silicon to systems. Important issues and limitation addressed at capacitor device, subsystem power density, and specific power, and full system efficiency levels.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Excellent data plotting motor and inverter efficiency for Accord vs. Prius approach. Good characterization of subsystems. Extensive benchmark testing of capacitors. What happened to ESL testing? No longer important?

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: We recognize the importance of accurate ESL measurements. We measured the ESL of the Prius film cap, which we utilized as our film capacitor benchmark with a technique currently utilized by industry but we found the technique somewhat limiting. Additionally, we have worked on alternative methods of measuring ESL dynamically by pulsing the capacitor and measuring the ripple frequency.

Our complete findings and measurement techniques will be presented in our TM report which will be available within the next few months.

Strengths: Excellent benchmarking data.

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Need to make sure benchmarking data is used by other investigation on their reports & technology assessment as in the Project Goal slides in the presentation. Also need to track if the benchmarking is leading to increased utilization, integration.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: ORNL: ORNL and other researchers have taken design and performance data from the benchmarking program and used it in motor models such as Motorsoft SPEEDCAD, Flux2D (FEA), and PSAT (ORNL/Sentech). Other researchers at ORNL have used the data to (1) perform fabrication and cost analyses for the Prius motor and (2) conduct thermal control studies using ORNL's HEATING 7.3 , a general-purpose, finite-difference conduction heat transfer model.

Presently ongoing within the Benchmarking project is an effort to improve the accuracy of another motor model using data obtained from no-load and back-emf tests. Since the empirical approach used in the performance tests ensured optimal operation, high-quality data was obtained that is well suited for this purpose. The model will effectively incorporate effects of saturation and the impact of variance in other parameters such as stator resistance and inductance, all of which fluctuate with speed, current, or temperature. The efforts to improve the motor model will aid in understanding the operational behavior of the 2006 Accord motor and other interior permanent magnet motors of similar design.

ANL: Analysis work has been performed at ANL using the Prius data provided to them by ORNL. ANL has taken the data and improved the accuracy of their motor models. They found the data to be of high value to their research.

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 10***

Title: **Benchmarking of Competitive Technologies/Component Characterization**

Presenter: **Bob Staunton/Larry Seiber** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: A good foundation work to set performance targets of power electronic and motor drives with extensively measured state of the art technologies.

Potential to Meet Technical Target: No

If no, explain: It's not a technology development project but help setting up goals

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Extensive testing of inverter and motor is very time consuming. It should help understand how state-of-the-art tractor motor drive works.

Approach sufficiently innovative: No
If no, explain: It's not a research or development type project.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Many component level performance have been reported. Inverter and motor were tested extensively.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Real test numbers have been reported; practical enough for future reference.

Weaknesses: Need some analysis work to support the test results and to understand the nature of the designs.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

ORNL collaborated with capacitor developers from SNL, PS, and ANL to support their development efforts in ceramic, glass ceramic, nano ceramic, and film capacitors. These developers supplied ORNL with test samples to evaluate. ORNL performed extensive tests on the prototypes delivered. The results were then feed back to the developers for comparison with their design and analysis data. For example, a significant benefit to the developers was ORNL ripple current test capabilities. Our test facility enables voltage, time and temperature to be controlled to a high degree of accuracy. So, instead of getting a 'go/no go' answer developers have been able to see specific improvements or worse performance between batches of capacitors supplied to ORNL for testing and see the effects of given process changes with their capacitor development efforts.

ORNL: ORNL researchers have taken design and performance data from the benchmarking program and used it in motor models such as Motorsoft SPEEDCAD, Flux2D (FEA), and PSAT (ORNL/Sentech). Other researchers at ORNL have used the data to (1) perform fabrication and cost analyses for the Prius motor and (2) conduct thermal control studies using ORNL's HEATING 7.3 , a general-purpose, finite-difference conduction heat transfer model. Presently ongoing within the Benchmarking project is an effort to improve the accuracy of another motor model using data obtained from no-load and back-emf tests. Since the empirical approach used in the performance tests ensured optimal operation, high-quality data was obtained that is well suited for this purpose. The model will effectively incorporate effects of saturation and the impact of variance in other parameters such as stator resistance and inductance, all of which fluctuate with speed, current, or temperature. The efforts to improve the motor model will aid in understanding the operational behavior of the 2006 Accord motor and other interior permanent magnet motors of similar design.

ANL: Analysis work has been performed at ANL using the Prius data provided to them by ORNL. ANL has taken the data and improved the accuracy of their motor models. They found the data to be of high value to their research.

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 7*

Title: **Cascade Multilevel Inverter for Fuel Cell Based HEV**

Presenter: **Burak Ozpineci** *Laboratory/Company:* **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification: Appears on target to address important FreedomCAR goals.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: The approach & relevance are closely linked, however, the design trade of increased switches & resulting control complexity is a serious issue.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Modeling and simulation effort well done. Experimental effort next year will reveal real challenges.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Comparison to standard six pulse inverter. Algorithm to control capacitor voltage.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Cascade Multilevel Inverter for Fuel Cell Based HEV**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Cascaded multilevel inverters are most applicable to medium voltage (2.3 kV, 3.3 kV, 4.16 kV, 6.6 kV...) AC drives. If the FreedomCAR tech roadmap included higher voltage 1 kV-2 kV then this makes more sense.

Potential to Meet Technical Target: No

If no, explain: Increases complexity.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: I don't agree with the application of MV techniques to low voltage drives in which complexity is increased.

Approach sufficiently innovative: No
If no, explain: Need cost analysis and comparator to buck/boost front end.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good simulation and modeling approach.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Can only justify project if FreedomCAR roadmap covers high voltage AC motors.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 5*

Title: **Cascade Multilevel Inverter for Fuel Cell Based HEV**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **3**

Relevance Justification: To the extent that a boost converter is required, this approach has the potential to reduce size and weight significantly. Not sure how cost will work out with extra switches.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: With this approach we are eliminating a transformer. A boost converter typically has four or more switches and these switches have to be rated for the full power (voltage and current) delivered to the motor. In the cascade multilevel inverter, we are adding twelve more switches (eight more than the boost converter), i.e. four switches per phase and each phase sees a third of the full power delivered to the motor; therefore, the switches do not have to be rated for the full power. This also means lower losses saving the operation costs.

A boost converter is typically operated at high switching frequencies more than 20 kHz, which causes substantial switching losses. The cascaded multilevel inverter can be operated at much lower switching frequencies (even at fundamental frequency) because of its stepped output voltage. This property also saves the operation costs.

This project began this year. A cost comparison will be made as the project progresses.

Approach Rating (1-4): **4**

Approach Justification: Very creative idea, good plan to start small and scale up.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Promising results shown by simulation. Demonstrated speed increase without field weakening. Would have been nice to see a preliminary cost analysis, to give an idea of the net cost advantage.

Accomplishments Sufficient: No, need preliminary cost analysis-other than this OK

Significant Accomplishments During Year: Demonstrated functional capability of approach with simulation.

PI's Response to Technical Accomplishments Questions/Comments: Please see the above comments for the cost argument. With the low-power prototype, we will be able have a better understanding of the savings achieved so that we can have a more quantitative cost analysis.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Add preliminary cost analysis. You don't need a complete packaged cost to do this; just base it on the cost difference, considering devices added/eliminated.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 5***

Title: **Cascade Multilevel Inverter for Fuel Cell Based HEV**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **2**

Relevance Justification: It is not yet clear if the cascaded multi-level topology will have a place in the EV, HEV, PHEV world.

Potential to Meet Technical Target: Yes

If no, explain: This is only a "yes" if the overall system benefits work in the favor of the cascaded system for combined control of the motor and the capacitors.

PI's Response to Relevance Questions/Comments: Our simulation results show that the benefits are in favor of the cascaded system. In the coming year, we will be building a low power prototype to demonstrate the benefits with experimental results.

Approach Rating (1-4): **2**

Approach Justification: While the current approach is ok, it seems that there is a need to look more at the total "system" impact of the various topologies.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Technical work to date is good, but there is a great need for understanding the impact of the multiple floating sources, their cabling, etc. The cost of the added switches needs to be considered, too.

Accomplishments Sufficient: Yes, still need system effects.

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Novel technology with lots of degrees of freedom for control.

Weaknesses: Need to be taking a careful look at system effects of having multiple power sources.

Recommendations for Additions/Deletions to Project Scope: Look at the floating sources and the cabling requirements.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 4*

Title: **Cascade Multilevel Inverter for Fuel Cell Based HEV**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: Cost trade off stated as a goal. Cost trade offs were not documented.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

With this approach we are eliminating a transformer. A boost converter typically has four or more switches and these switches have to be rated for the full power (voltage and current) delivered to the motor. In the cascade multilevel inverter, we are adding twelve more switches (eight more than the boost converter), i.e. four switches per phase and each phase sees a third of the full power delivered to the motor; therefore, the switches do not have to be rated for the full power. This also means lower losses saving the operation costs.

A boost converter is typically operated at high switching frequencies more than 20 kHz, which causes substantial switching losses. The cascaded multilevel inverter can be operated at much lower switching frequencies (even at fundamental frequency) because of its stepped output voltage. This property also saves the operation costs.

This project just began this year. A cost analysis and tradeoffs will be made as the project progresses

Approach Rating (1-4): **3**

Approach Justification: Is it cost effective to use Si to replace transformers?

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Please see the above comments for the cost argument. With the low-power prototype, we will be able have a better understanding of the savings achieved so that we can have a more quantitative cost analysis.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Need cost trade off.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Cascade Multilevel Inverter for Fuel Cell Based HEV**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Power electronics that can meet the cost and temperature tolerance goals of the FreedomCAR program are critical to the success of the program and for OEMs to be able to offer HEVs that are affordable and can meet customer needs.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Early in the project but approach is reasonable and based on analysis, simulation and modeling. Technical approach is intriguing but complex.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good progress after less than a year of work on this project. Design seems promising in its innovation.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: New innovative design alternative to existing designs.

Weaknesses: Design is complex and may prove to be costly to produce. Existing inverters tend to be expensive so it is difficult to see how this can result in reduced costs, but the design is intriguing enough to continue work and develop hardware to evaluate a working design.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **Cascade Multilevel Inverter for Fuel Cell Based HEV**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **3**

Relevance Justification: Complex power flow control.

Potential to Meet Technical Target: No

If no, explain: Not matured enough.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Interesting project.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 7***

Title: **Cascade Multilevel Inverter for Fuel Cell Based HEV**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes
Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:
Weaknesses:
Recommendations for Additions/Deletions to Project Scope:
Additional Comments:
PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 8*

Title: **Cascade Multilevel Inverter for Fuel Cell Based HEV**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Cost and complexity of system.

Potential to Meet Technical Target: No

If no, explain: Still to early to tell.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 10***

Title: **Cascade Multilevel Inverter for Fuel Cell Based HEV**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification: Cascade topology may allow EMI reduction modularized design, etc. It's not clear if the design can be accepted for traction drive but it's worthy of pursuing. Fuel cell is likely to be low voltage - cascade is a way to increase voltage level.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: Good comment. We impose certain conditions to the controller to keep the capacitors charged. We are also keeping the drive cycle considerations in mind so that in every situation the capacitor voltage will be balanced while supplying the required power.

Approach Rating (1-4): **4**

Approach Justification: Need to study charge balancing, especially for the drive cycle design consideration. Other than that the approach is good.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Still in conceptual stage. Need substantial effort in control and design optimization. Concept is good. Implementation and application are not yet clear.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Need practical implementation and design verification.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: A novel cascade inverter circuit is conceived.

Weaknesses: No controller implementation is done to convince audience its feasibility.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 7*

Title: **Cascade Multilevel Inverter for Fuel Cell Based HEV**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification: Project shows significant promise in meeting FreedomCAR goals through innovative design.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Splitting of std. inverter functions into a master for fuel cell + 3 bridges for ultracaps was very exciting as was the elimination of magnetics (which can significantly reduce cost, package size and thermal concerns). Could integrate well with Wide bandgap work.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Characterization of speed, voltage, torque, current, and cap-charging are excellent and clearly show the advantages of the approach. Look forward to seeing hardware and real characteristics of the new inverter design.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Demonstrated advantages of this approach through simulation.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Excellent, innovative, design.

Weaknesses: Would like to see packaging scheme & actual hardware.

Recommendations for Additions/Deletions to Project Scope: See if this can combine w/wide bandgap device for additional improvement.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: FY06 work was to develop the concept. In FY07, we will be building a low power hardware prototype to evaluate its operation. Next year, in the merit review, we will present the test results.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **DC to DC Converter for Fuel Cell and Hybrid Vehicles**

Presenter: **Lizhi Zhu** ***Laboratory/Company:*** **Ballard**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification: Primarily technology demonstration and integration. Not heavy on innovation. Suitable for industrial activity.

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Incremental technical approach. (i.e. Advancing performance by incremental engineering). Sound industrial effort unclear if approach can stretch technical objectives to 105ºC.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Engineering goals proceeding ok. Technology goals lagging. To be fair, the effort is producing a "real" converter with requirements beyond expectations of a S&T project.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Engineering experience between alpha beta models.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **DC to DC Converter for Fuel Cell and Hybrid Vehicles**

Presenter: **Lizhi Zhu** ***Laboratory/Company:*** **Ballard**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: FreedomCAR programs in HEV, PHEV, and FCHV have strong need for galvanically isolated DC-DC converters.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Good approach for high voltage >200 V to low voltage 14 V. Approach leads to meeting targets.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Appropriate focus on thermal requirements and influence on material usage. Shaving cost from the housing & heatsink may be difficult in light of potential leaks.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: I'll second Prof Peng's comment on comparison to Prius DC-DC converter. Can we project the trend in temperature of coolant and DC-DC power rating to estimate where Toyota will be in 2010 relative to FreedomCAR targets?

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 5*

Title: **DC to DC Converter for Fuel Cell and Hybrid Vehicles**

Presenter: **Lizhi Zhu** *Laboratory/Company:* **Ballard**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: Due to the various voltages in these vehicles, the need to effectively convert between levels is important.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Iteration to improve from first generation device was a good step forward.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Recovering from high pressure drop, leaky initial design to create a more viable concept was good.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Consideration of manufacturing issues along with component costs.

Weaknesses: Question if connector cost at high voltage end has been properly accounted for. This area is typically a challenge.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 5*

Title: **DC to DC Converter for Fuel Cell and Hybrid Vehicles**

Presenter: **Lizhi Zhu** ***Laboratory/Company:*** **Ballard**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **2**

Relevance Justification: Meets goals @ 90ºC Inlet cooling but goal is changing to 105ºC, then to air cooling. Will this technology apply to the changing goals?

Potential to Meet Technical Target: Yes/No

If no, explain: Meets goals, but goals are changing. Would an OEM want today's technology to 2012?

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Achieved goals but the goals are changing, maybe the technology stretch was not great enough.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Thermal shock for power devices (or semiconductor packages) is 1000 cycles - why was thermal shock stopped after 100 cycles ?

Accomplishments Sufficient: Yes
Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **DC to DC Converter for Fuel Cell and Hybrid Vehicles**

Presenter: **Lizhi Zhu** ***Laboratory/Company:*** **Ballard**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: Power electronics that can meet the cost and temperature tolerance goals of the FreedomCAR program are critical to the success of the program and for OEMs to be able to offer HEVs that are affordable and can meet customer needs.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Good methodical approach that provides balance of technical advancement with practical realities of making a product that could go into auto production at some time in the future.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Met all but two goals and for those goals laid out a reasonable plan to meet the goals there as well.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Good project that either met all goals or laid out a roadmap to meet the goals.

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 6***

Title: **DC to DC Converter for Fuel Cell and Hybrid Vehicles**

Presenter: **Lizhi Zhu** ***Laboratory/Company:*** **Ballard**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: A good engineering project with several innovative ideas.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM **Reviewer's Ability to Rate (1-10): 7**

Title: **DC to DC Converter for Fuel Cell and Hybrid Vehicles**

Presenter: **Lizhi Zhu** ***Laboratory/Company:*** **Ballard**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM | ***Reviewer's Ability to Rate (1-10): 8***

Title: **DC to DC Converter for Fuel Cell and Hybrid Vehicles**

Presenter: **Lizhi Zhu** ***Laboratory/Company:*** **Ballard**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 10*

Title: **DC to DC Converter for Fuel Cell and Hybrid Vehicles**

Presenter: **Lizhi Zhu** ***Laboratory/Company:*** **Ballard**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Work is very thorough. Integration is the key to performance improvement cost reduction, and reliability improvement.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Thorough consideration on cost, reliability, cooling, and manufacturing.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Most performance indexes already exceed DOE target.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Integration and manufacturing.

Weaknesses: Not obvious.

Recommendations for Additions/Deletions to Project Scope: Time for manufacturing.,

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 8***

Title: **DC to DC Converter for Fuel Cell and Hybrid Vehicles**

Presenter: **Lizhi Zhu** ***Laboratory/Company:*** **Ballard**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Strong need for cost effective, reliable, high efficiency DC/DC converter for HEV/FCV. This hardware looks to be near commercial availability for actual use.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: α→β design changes have addressed the barriers in the α design to meet the DOE goals.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: β design improves the coolant temp, volume, and coolant pressure drop to above FreedomCAR goals and also improves cost estimation and weight over the α version without sacrificing power or efficiency.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: β design near ready for commercial introduction.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Excellent β design.

Weaknesses: Still need to do some cost & weight reduction to meet DOE goals.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 6***

Title: **Development of Improved Powder for Bonded Permanent Magnets**

Presenter: **Iver Anderson** ***Laboratory/Company:*** **AMES**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Gives opportunity for more effective magnet shapes and magnetizing directions - these provide designers with extra "degrees-of-freedom" to optimize IPM designs. Definitely helpful for cost reduction, but somewhat offset by torque density penalty.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Looks like a good plan with short and long-term benefits.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Demonstrated potential for improving magnetic properties at high temp.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Development of 150°C bonded material and fluoride coating demonstration.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments: The "macro" deliverables look good here, from a machine designer point of view. I can't offer many suggestions on the "micro" materials mgf. research due to lack of experience in this area.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 6***

Title: **Development of Improved Powder for Bonded Permanent Magnets**

Presenter: **Iver Anderson** ***Laboratory/Company:*** **AMES**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: These material developments are crucial for the advancement of high performance, reliable, low cost motors.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: The only thing keeping this from being a "4" rating is that there seems to be a need for more work with a motor manufacturer to evaluate the impact of Iver's work on the actual motor performance.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: It is possible that the new APEEM motor research RFP will result in the award of a contract to a commercial firm that can provide a new set of desired magnet specifications and can test the bonded magnets that we provide for them in an appropriate PM electric machine.

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Improvements that allow flat characteristics with temperature and manufacturing cost advantages are highly desirable.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: The potential to do anisotropic materials with more energy density is very cool.

PI's Response to Technical Accomplishments Questions/Comments: We are wholeheartedly in favor of motor testing of our bonded magnets, particularly if the high temperature performance (up to 200°C) can be compared. Some extensive discussions have been conducted with UQM about motor design involvement and the result was the joint preparation of a white paper that was submitted in late April of 2006, soon after the Motor/Magnet Workshop that we organized and hosted at Ames Lab, with the assistance of ORNL.

Strengths: Cutting edge material / process development of a critical component, including a focus on cost.

Weaknesses: Motor design involvement should be more integral to the work.

Recommendations for Additions/Deletions to Project Scope: Motor design involvement should be more integral to the work.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Development of Improved Powder for Bonded Permanent Magnets**

Presenter: **Iver Anderson** ***Laboratory/Company:*** **AMES**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Project is strongly focused on raising coercively of bonded PMs and of regaining flux capability.

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Solid approach of spin melt (near term) and gas atomization longer term & commercialize.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Capable of doing multiple sample runs/day to validate compositions.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: AMES Lab are the experts, very impressive group.

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: I'd like to see this project reach commercialization stage. The needs are very great and by 2009; the HEV and PHEV markets will demand better and low cost PMs.

Additional Comments: Push to commercialize.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: We are pushing hard to make the reviewer's desire into reality. Much effort has been spent on industrial collaboration and we will continue in this outreach mode until commercialization is accomplished. A major accomplishment of this project has been the close collaboration of our project with Arnold Magnetic Technologies for bonded magnet compounding, molding and commercial testing capabilities. The reviewer also should know that Magnequench International was pursued for licensing discussions concerning our new magnet alloy (patent application filed) for nearly 12 months, before the large disruptions of a total move of MQI to off-shore research and production and a high level management change completely derailed our attempts. Spherical (gas atomized) powder producers have been approached more recently about the benefits and risks of this technology and several expressions of interest are being pursued, as new results continue to accumulate.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 7***

Title: **Development of Improved Powder for Bonded Permanent Magnets**

Presenter: **Iver Anderson** ***Laboratory/Company:*** **AMES**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: A long-term high-risk R&D.

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient:

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Development of Improved Powder for Bonded Permanent Magnets**

Presenter: **Iver Anderson** ***Laboratory/Company:*** **AMES**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Research is very relevant to the mission of the FreedomCAR program and the needs of the OEMs for lower cost, compact, lightweight motors.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: PI is doing work in areas that few other researchers are doing. PI has identified relevant and strong partners for collaboration.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: PI is making progress and getting data but the pace is slightly slower than we would like to see.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Presentation provides good engineering info and results data that are lacking in many other presentations. PI did a good job of providing background info as well as sufficient engineering detail in results.

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 6*

Title: **Development of Improved Powder for Bonded Permanent Magnets**

Presenter: **Iver Anderson** ***Laboratory/Company:*** **AMES**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes
Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10):*** ***Reviewer did not provide number.***

Title: **Development of Improved Powder for Bonded Permanent Magnets**

Presenter: **Iver Anderson** ***Laboratory/Company:*** **AMES**

Research is Important to FreedomCAR (1-10): Reviewer did not provide number.

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient:

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D **Reviewer's Ability to Rate (1-10): 7**

Title: **Development of Improved Powder for Bonded Permanent Magnets**

Presenter: **Iver Anderson** ***Laboratory/Company:*** **AMES**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification: Advanced permanent magnet is always a plus to the motor performance. This project addresses temperature, flux, and manufacturing issues for better bonded magnet.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Develop PM alloy for high temperature with reasonable flux; develop manufacturing process; work with motor manufacturer to use the new material in manufacturing.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good results in PM itself in terms of temperature range and manufacturing but should have results tied to actual machine performance.

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Project milestones (for FY2005) contained deliverable for fabrication and shipment of bonded magnet samples to ORNL for motor testing, based on our mutual interests in collaboration. This was accomplished within the specified time and resulted in high quality bonded magnets that were received at ORNL. A second shipment also was received at ORNL during FY2006 to permit head to head comparison of bonded magnets made from a benchmark commercial alloy and from a very good Ames Lab magnet alloy design, both types processed from melt spun particulate. Unfortunately, the ORNL researchers were not able to test either of the bonded magnet samples in their experimental electric motor during FY2006 due to a lack of funds.

Strengths: Improve PM temp range and manufacturing process.

Weaknesses: Did not show actual performance when used in an actual PM machine.

Recommendations for Additions/Deletions to Project Scope: Add a task that shows performance improvement with the material with actual PM machine and better compare it with an existing design.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: The lack of a test in an actual PM machine was not due to any action on the part of Ames Lab. We are wholeheartedly in favor of motor testing of our bonded magnets, particularly if high temperature performance (up to 200°C) can be compared.

A new motor collaborator probably must be located for this task, if ORNL cannot provide this type of testing under their current project statement of work. It is possible that the new motor research RFP will result in the award of a contract to a commercial firm or an alternate laboratory that can provide a new set of desired magnet specifications and can test the bonded magnets that we provide for them in an appropriate PM electric.

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 8*

Title: **Development of Improved Powder for Bonded Permanent Magnets**

Presenter: **Iver Anderson** ***Laboratory/Company:*** **AMES**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Operation of power electronics systems at 105°C coolant will require magnetic materials that can stand up to elevated temperature with low loss. These magnets provide a strong way forward.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Very innovative materials selection for alloy composition. Excellent evolution from melt spinning → gas atomization for improved cost metrics and easier manufacturing.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good hysteresis demonstrated for the WT-102 material chosen for lower quench rates to attempt gas atomization. Process development for gas atomization.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Process & alloy selection for gas atomization.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Good technology & alloy development and characterization. Good process development for gas atomization.

Weaknesses: Cost needs to be addressed.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Most meaningful comparison of cost needs to be made between finished rotor costs for electric motors with equivalent output and efficiency that has contain either bonded isotropic injection molded magnets or sintered aligned magnets (the current approach for Prius motors). This comparison should test the maximum advantage of complex shaped bonded isotropic magnets for boosting reluctance torque and should provide a realistic comparison to a magnetic torque dominant machine that uses simple shapes of sintered magnets, with both machines maintaining performance over a wide temperature range. Apparently, a true cost comparison must involve a significant consideration of motor design and manufacturing issues, as well as accounting for magnet durability and motor temperature tolerance. Please see white paper that was submitted in late April 2006 for additional details of this proposed work.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 10***

Title: **Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**

Presenter: **Michael O'Keefe** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: This system's engineering level project is necessary and adds rationale to APEEM focused projects in machines, power electronics, and thermal controls.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: PHEV content takes this project into energy storage areas. How coordinated is the project with USABC?

Approach sufficiently innovative: No

If no, explain: When PHEV is included in project scope we need to see the overlap with energy storage projects and findings.

PI's Response to Approach Questions/Comments: At this time, we are focusing only on the power electronics and electric machines (PEEM) aspects of the problem. However, ultimately, it is to our benefit to lay out the process of interaction on these cross-cut issues. In as much as the PEEM system will affect the energy storage system and vice-versa, it is beneficial to coordinate. I do feel that we can begin making progress without bringing the battery projects in but perhaps this is an area to begin a dialogue in during this coming fiscal year (FY07). In addition to energy storage, strictly speaking on the thermal cooling side, there are opportunities and needs to coordinate with engine and engine cooling research and activities, energy storage and energy storage activities, the APEEM team and cooling activities (the main focus of NREL's work), and possibly even cabin thermal comfort and passenger heating/cooling activities.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Doing drive cycle comparisons of HEV and PHEV becomes very contingent on what engine strategy is used and what energy management algorithm is used. The results can vary widely based on such interactions.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: This is correct. This is also why this project must continue to remain coordinated with the vehicle systems analysis team's efforts and the best thinking regarding to these issues from that team.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Must add in clarification of vehicle propulsion system top level control approach. Some strategies put heavier burden on the electric subsystem and may provide higher overall efficiency but at the expense of reduced component life.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Again, for this, we will be deferring to the guidance of the vehicle systems analysis technical team, though we hope to be able to close the loop and provide them feedback on the interaction between high-level vehicle control and component life.

Thank you to this reviewer. These are helpful and constructive comments.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**

Presenter: **Michael O'Keefe** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **3**

Relevance Justification: A systems view of thermal mgmt. is definitely needed to make good use of the subsystem and component developments. The project definition, however, makes it hard to assess the value in meeting FreedomCAR targets.

Potential to Meet Technical Target:

If no, explain: See justification above.

PI's Response to Relevance Questions/Comments: Moving into FY07, we intend to become more coordinated with the other APEEM projects and teams. This will demonstrate where the application of a system's view of thermal management will bring value by helping us to know what thermal cooling R&D needs to be developed.

Approach Rating (1-4): **2**

Approach Justification: The plan seems to start well, but it's not clear how it adds value in the end. Need a better roadmap on how it all ties together. Too fuzzy to me.

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments: A concrete end point will be to have a full understanding of the requirements for cooling technologies that best enable APEEM components to meet cost, life, volume, and weight goals and additionally knowing what the best match from our portfolio of thermal control technologies for those requirements would be. Putting it another way, we want to develop the know-how of what are the best cooling solutions for the APEEM program R&D projects both present and future.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Good comparison of HEV and PHEV PEEM efficiency. I expected to see more conclusions drawn about thermal control needs vs. portfolio.

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: We are just completing an initial look at the comparison of the thermal control portfolio. These results will be available in the near future.

Strengths:

Weaknesses: Lack of application for learning.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Weakness: Lack of application for learning statement - I'm not sure I understand this comment fully. The approach we're taking with this project is to start small, have relevant quick-hit successes, increase coordination with others as we move forward, and share those results with the team and thus including feedback and learning as we go—a give and take process.

Thank you for the constructive comments.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 1***

Title: **Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**

Presenter: **Michael O'Keefe** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Another system level study. Needed and useful to guide S&T investment. Risk is that conclusions could be compromised by conventional wisdom.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: Our hope is that by frequently releasing results for review and coordinating with others, we can avoid being compromised by "conventional wisdom". I think the main justification for this project is that "we don't know what we know". That is, nobody has pulled together and translated the FreedomCAR needs into thermal requirements and nobody has yet translated the thermal cooling performance into their effect on FreedomCar goals. So saying, the reviewers' comments will be taken to heart because in the immortal words Mark Twain: "It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so."

Approach Rating (1-4): **3**

Approach Justification: System study requires modeling and simulation, which is the technical approach. How about validation? Getting validation tough on fixed budget.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: My thoughts on validation are to supplement with experimentation where possible. This goes right back to the need to be coordinated with others on the team and to take advantage of experimental efforts that are already planned so as to get a good validation on the modeling and simulation efforts. This is a great comment and I agree the issue of validation is of great importance arriving at correct conclusions. Experimental validation also helps to erase some of the concern with "conventional wisdom" mentioned in the justification section above.

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Data interesting and revealing. Validation my chief concern.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Contrasting thermal loading between conventional HEV and plug-in HEV. Accounting for drive cycle.

PI's Response to Technical Accomplishments Questions/Comments: See above.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 8***

Title: **Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**

Presenter: **Michael O'Keefe** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: The assignment of a continuous rating to components (such as inverters and motors) needs to have the benefit of this sort of work looking at duty cycles.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: Thank you. We hope to develop two-way collaborations with the other principle investigators to help provide them with duty cycles and have them give us feedback on thermal requirements.

Approach Rating (1-4): **3**

Approach Justification: Modeling for a range of conditions (drive cycles) is a good start, but it needs to be taken upstream to the actual losses and temperature impact on the components.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: Yes, we hope to begin this in the coming year.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: The data is good to assimilate as part of the whole system, but to make real use of it requires looking at the impact / effect on individual components.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Need loss analysis.

PI's Response to Technical Accomplishments Questions/Comments: This is our intention.

Strengths: Great to be looking at the whole system.

Weaknesses: Need to get to the impacts on the components (inverters and motors, for example).

Recommendations for Additions/Deletions to Project Scope: Work the data back to the losses and thermal effects on the powertrain components.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: This is our intention with upcoming work.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**

Presenter: **Michael O'Keefe** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **2**

Relevance Justification: APEEM is power electronics and motor not vehicle. It appears this is looking at the vehicle loads to determine inviter and motor loads. Why not ask the designers what their power losses will be to meet the 55 kW target.
Where is the technology?

Potential to Meet Technical Target: No

If no, explain: Does not appear to be tied to goals.

PI's Response to Relevance Questions/Comments: The reviewer is correct in that one of the two main thrusts of this project is to use vehicle systems analysis to determine motor and inverter duty cycles and thus, thermal cooling requirements. This necessarily becomes a cross-cut or interfacing activity with the vehicle systems tech team as we are not creating vehicle models under this project. We intend to bring designers into the loop where possible, however, remember that we are dealing many times with new equipment and motor/inverter designs. It is my understanding that the peak loss requirements are not always know. Additionally, the link between thermal cycling and life/reliability is surely an unknown. The other major thrust of this activity is to translate the R&D portfolio of APEEM thermal cooling technologies into their weight, cost, volume, and life/reliability implications when implemented in a vehicle system. We're looking at the APEEM cooling requirements from both sides of the problem. I feel strongly that this is the proper approach.

Approach Rating (1-4): **2**

Approach Justification:

Approach sufficiently innovative: No
If no, explain: Models not technology.

PI's Response to Approach Questions/Comments: Perhaps this is referring to the issue of validation? We intend to not only deal with models but to also validate systems. The thermal modeling will be closely tied to the PI's who are doing experimentation and research on their respective thermal control technologies and also to others working on PEEM components. Thus we are not going to deal only with models and hope to have some thermal system level experimental validation as well. To the point of which models we are developing, see the comments below.

Technical Accomplishment and Progress Rating (1-4):

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year: There are lots of models on HEV performance under various drive cycles - why do it again. Adapt an existing model.

PI's Response to Technical Accomplishments Questions/Comments: We are using models provided by the vehicle systems analysis team and are thus not developing new models of the vehicle. Model development is focused on thermal models of the thermal control technologies and the interface to the PEEM components which provide the thermal loads.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**

Presenter: **Michael O'Keefe** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **3**

Relevance Justification: While thermal management is important for the FreedomCAR program to meet its goals, it does not appear that this research project will substantially contribute to the knowledge base or assist in meeting the goals. Analytical models are important but need to be focused in areas that are critical to meeting FreedomCAR goals.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: I respectfully disagree with the reviewer's point of view. The reviewer admits that thermal management is important for the FreedomCAR program to meet its goals. This project is critical in mapping FreedomCAR vehicle and APEEM level goals into thermal requirements and going the other way to translate the application of thermal control R&D into their affect on PEEM system weight, cost, volume, and life/reliability.

Approach Rating (1-4): **2**

Approach Justification: Diversion to vehicle level modeling and distraction into PHEV work seem irrelevant to the task described in project objectives. Need to take analysis work further & deeper to better understand motors and inverters.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: The point is well taken though I do feel strongly that a vehicle systems perspective needs to be maintained while conducting this research. Cooling is only relevant to components in a given context (duty cycle, size requirement, etc.). To be able to properly attribute cost, life, weight, volume, etc. for thermal control technologies, we need to know how they would be used. For this we need to understand the interaction between vehicle and component. We will be interfacing with the vehicle systems team for the strict vehicle level analysis—thus, this project will not be focusing on any vehicle modeling, only the interface to the vehicle systems team who is already doing that modeling.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: The FreedomCAR thermal management program needs more detailed systems and subsystems modeling -- more than total vehicle modeling.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Agreed and we intend to work towards this.

Strengths: PI and lab have excellent modeling and thermal management capabilities.

Weaknesses: Need to focus on the subsystems more so than vehicle and avoid diversion into PHEV -- unless DOE requests this redirection.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Weakness: Agreed, I would restate that we need to keep the link or tie to the vehicle level and move the focus to the component level as time goes on.

Thanks for the good constructive comments.

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): Reviewer did not provide a number.*

Title: **Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**

Presenter: **Michael O'Keefe** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): Reviewer did not provide number.

Relevance Rating (1-4): **2**

Relevance Justification: Needs motor and inverter analysis (no analysis of motor & inverter).

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: The results presented during the annual review did in fact include a simulation of the motor and inverter system to look at thermal load generation. Also, a slide giving the results of various thermal control technologies evaluated using an inverter thermal model was presented. The intent of the project in FY07 is increasingly include more system components and interactions as well as to begin addressing cost, weight, volume, and life/reliability concerns.

Approach Rating (1-4): **2**

Approach Justification:

Approach sufficiently innovative: No

If no, explain:

PI's Response to Approach Questions/Comments: The approach of this research is two-fold: first, to understand the thermal cooling requirements for power electronics and electric machines (PEEM) components by using a systems context of how the PEEM systems will operate in real vehicles. That is, use vehicle systems models to determine PEEM system duty cycles and associated heat generation. Second, we seek to evaluate the portfolio of thermal control technologies in the context of PEEM systems in a vehicle environment for their ability to meet cost, weight, volume, life/reliability, and cooling performance goals.

Technical Accomplishment and Progress Rating (1-4): **1**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: During FY06, we used vehicle systems models to determine preliminary cycle-average and peak cooling requirements for various advanced powertrains and have also begun evaluation of the portfolio of cooling technologies being considered under the APEEM program in the context of the peak temperature of silicon devices on an inverter model.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 7***

Title: **Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**

Presenter: **Michael O'Keefe** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification: Can be relevant if focused on motor inverter duty cycle and heat generation.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: This is our intention.

Approach Rating (1-4): **2**

Approach Justification: Focus on sub-systems! Assess all implications (wt, vol.) for each alternative technology approach.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: Again, this is our intention to focus on the sub-systems. We intend to include weight, volume, and other elements such as cost and life/reliability. These are challenging to assess but we are making progress. Stay tuned for more results.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Don't dwell on vehicle architectures. Parallel and series hybrids will sufficiently flush out the best thermal solutions.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: This is a good comment. There is a diminishing returns with the number of architectures examined versus the new information obtained with each new analysis. However, the examination of the vehicle architectures is fairly easy since we are coordinating with the vehicle systems team and capitalizing off of the work that's already gone into that effort. This project is not spending time in vehicle model development. I feel the vehicle powertrains presented sufficiently cover the design space to give us a good feel for the possible applications of thermal control technologies.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 8***

Title: **Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**

Presenter: **Michael O'Keefe** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification: Need inverter and motor analysis not at the vehicle.

Potential to Meet Technical Target: No

If no, explain:

PI's Response to Relevance Questions/Comments: The vehicle analysis is used to determine the duty cycles for the subsequent inverter and motor analysis. We will be focusing more on the inverter/motor analysis as time goes on.

Approach Rating (1-4): **1**

Approach Justification:

Approach sufficiently innovative: No
If no, explain: Project has great potential if it focuses on components.

PI's Response to Approach Questions/Comments: This is our intention to focus on the thermal requirements for cooling power electronic and electric machine (PEEM) components. To properly do so, we need to know what the PEEM cooling requirements are, which is why we are evaluating PEEM systems in the vehicle context. Work is ultimately aimed at cooling the PEEM components while being aware of how our cooling systems could potentially be tied in with other cooling networks (engine cooling, energy storage cooling, etc.—this is more long-term).

Technical Accomplishment and Progress Rating (1-4): **1**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Along the lines of component performance, we have completed a preliminary analysis this year of how the portfolio of thermal control technologies performs in terms of cooling an inverter under worst-case conditions. This analysis will be expanded with time to include other relevant metrics such as the cost, weight, volume, and life/reliability impacts of the various thermal control technologies. We intend to also look at the motor in the future.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 9***

Title: **Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**

Presenter: **Michael O'Keefe** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **3**

Relevance Justification: Very important to have a methodology to select which thermal technologies provide the hybrid "impact" toward meeting FreedomCAR goals, to focus further research efforts. This provides the focus necessary to ensure that the needs are being met cost effectively, without researching things that may be interesting but are not needed to achieve FreedomCAR goals.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: The focus of flowing duty cycle to thermal requirements is a very effective technical approach to addressing what are the power and thermal requirements for FreedomCAR. Important that the program is looking at differences between CV, HEV, FCV, and PHEV. Need to develop criteria for assessing thermal project against needs.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Begin analysis of duty cycle-performance relationships. Excellent differentiation of CV, HEV, PHEV, and FCV.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Conversion of duty cycle to thermal & power requirements.

Weaknesses: Needs to define approach for assessing thermal projects against FreedomCAR needs.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: We are beginning this effort with earnest and hope to have results soon. We are starting small looking at the thermal control technologies evaluated to show the temperature rise in an inverter under steady-state worst case conditions. The peak temperature related directly to the life/reliability of the inverter and thus to FreedomCAR targets. We will continue growing in this area so as to better assess the direct impact of thermal control technologies on FreedomCAR technical targets: the weight and volume increases for thermal control technologies, the cost increases, the impact on life/reliability, etc. This is, of course, the great challenge with this area of research but we intend to tackle it by starting with small, quick-hit, relevant projects that provide frequent results that can be reviewed by the team. We hope to grow our coordination/collaboration with others as time moves on.

Thanks for the constructive feedback.

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 7***

Title: **Dynamic & Steady State Modeling to Identify, Over Various Drive Cycles…**

Presenter: **Michael O'Keefe** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: I believe the goals of this work are fundamental to the FreedomCAR program.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: From my perspective, it seems that researchers have taken appropriate approaches from the global to micro approach.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: System level models incorporating specific thermal control models is real useful and important.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry **Reviewer's Ability to Rate (1-10): 10**

Title: **Embedded Capacitor Development Activities**

Presenter: **David Kaufman** ***Laboratory/Company:*** **ANL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Determine applicability of PLZT on copper to future power inverters in terms of size, voltage withstand, and temperature.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: The evaluation of Cu bottom electrode foils will be part of FY07s efforts. While using Cu foils will not significantly effect size it will reduce cost, ease manufacturability, and better integrate our technology with standard PWB fabrication.

Approach Rating (1-4): **4**

Approach Justification: Complete program laid out and metrics established to validate performance against targets.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Appears on track and if risks are managed, should result in very valuable contribution to FreedomCAR portfolio.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Need to understand influence PWB flexing and vibration modes will have on the embedded capacitor.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: The influence of flexing and vibration are important considerations that are already included in our list of necessary component tests. Indeed, Delphi has facilities for doing just these sort of evaluation.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 4***

Title: **Embedded Capacitor Development Activities**

Presenter: **David Kaufman** ***Laboratory/Company:*** **ANL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification: The project attacks energy density and integration at the same time. Might have better chance of stretching to program goals.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Approach seems focused on materials S&T, although with a practical awareness. Component development is tenuous.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: This year marks an important transition from proof-of-concept of our approach towards component development. A primary piece of this transition has been embarking on partnerships that will transition basic laboratory development towards capacitor component fabrication. Our industrial partners are experts on component design and have a proven track record. Component development forms the heart of our continued efforts and will be presented at next year's program review.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: The project appears to be on track. However, many show stopping milestones appear to be ahead. Discussion of leveraging other resources raises concern of dependence on leverage to make progress on SOW.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: It has always been our intention, consistent with the desires of DOE and the EETT, to form partnerships that will enable our technology to be commercially manufactured. Our work, as a national laboratory, is to establish the basic S&T and work with US companies to take this further. Rather than expend our efforts 'rediscovering the wheel', we have complemented our resources with expertise already held by our industrial partners. This speaks directly to our mission and SOW.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **Embedded Capacitor Development Activities**

Presenter: **David Kaufman** ***Laboratory/Company:*** **ANL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Research to find high temperature tolerant, low cost, easily manufactured capacitors is critical to meeting the goals of the FreedomCAR program and to the ability of OEMs to offer affordable, fully functional HEVs to customers.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: The approach taken is logical and data based. The PI has evaluated materials in the lab and is now making component hardware.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Accomplishments are very good. The PI has listened to past comments and followed through to incorporate those recommendations into his research plan.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Good analytical work substantiated in hardware.

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: As Bartels and James used to say "We thank you for your support". Thanks for your time in evaluating our project.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Embedded Capacitor Development Activities**

Presenter: **David Kaufman** ***Laboratory/Company:*** **ANL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: The Holy Grail.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Persistent in Tackling Technical Challenges as they arise.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 4***

Title: **Embedded Capacitor Development Activities**

Presenter: **David Kaufman** ***Laboratory/Company:*** **ANL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Appears to be a promising project. Tech team would like to see the capacitor designs for evaluation by experts.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: We understand the Tech Teams concerns and desires to evaluate the component design. Our industrial partners are experts on component design and have a proven track record. Specific design details will be a significant part of next year's efforts in our partnership and will be presented at next year's program review.

Approach Rating (1-4): **4**

Approach Justification: The approach used did not assure that the developed technology is capable of assembling bulk capacitors.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: The evaluator's comment regarding 'bulk capacitors' is not understood. The basis of our technology is a thin film embedded capacitor architecture. We have shown that our technology can meet the high voltages needed for automotive applications. The capacitance will be obtained by appropriately stacking embedded foils in a parallel capacitor design. Together with our industrial partners we are confident that automotive requirements will be satisfied.

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 8*

Title: **Embedded Capacitor Development Activities**

Presenter: **David Kaufman** ***Laboratory/Company:*** **ANL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: We do though need to get more detail on design to be confident that this is on the right track.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: Our industrial partners are experts on component design and have a proven track record. Specific design details will be a significant part of next year's efforts in our partnership and will be presented at next years program review.

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 9***

Title: **Embedded Capacitor Development Activities**

Presenter: **David Kaufman** ***Laboratory/Company:*** **ANL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Embedded capacitors for power electronics promise significant advantages in weight, cost, size, and reliability (no solder joint). They provide long-range advantage for meeting FreedomCAR goals. Embedded capacitor technology is well established for low power in PWBS, medium risk in extending to high dielectric constant , high voltage applications.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: PLZT/LNO/metal provides good energy density and high voltage at reasonable cost through incorporation in a low cost manufacturing process, especially if the metal can be shifted from Ni to Cu. Controlled environment processing of PLZT on Cu uses known & established processes so has limited risk.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Continued development of PLZT/LNO/Ni processing and implementation of strategy for Cu metalization & coating, but would have been nice to see what new data they had on the Ni version since the last review and what progress they have made on making the Cu.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Due to the limited presentation time we chose to lay out the larger program directions and ability to provide an innovative and significant solution to (P)HEV needs. It was important to discuss our industrial partnerships and steps to commercial components, and regrettably this came at the expense of delving into more depth on specific experimental accomplishments. Work on Cu is the backbone of FY07s efforts and will be shown in next years review. We are happy to provide continued updates on the development.

Strengths: Size, weight, cost advantages are significant.

Weaknesses: Not clear what developments have been made this year in the Ni process or on the Cu process. Need more test data to be presented.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Development of LNO barrier layer to solve the interface problem between Ni substrate and PLZT is one of the significant developments made in 2006. Another important development is the optimization of processing/fabrication methodology to fabricate PLZT films on Ni/LNO with high k values.

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 10*

Title: **Embedded Capacitor Development Activities**

Presenter: **David Kaufman** ***Laboratory/Company:*** **ANL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Package allows PCB integration with very high capacitance at high voltages.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Making it PCB integratable is good for parasitic and interconnect reduction.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Show potential performance and size form factors. Need to have actual integration with inverter testing.

Accomplishments Sufficient:

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Integration with inverter testing and prototypes are the primary goals of our continued efforts and will be shown at next years review.

Strengths: Large size sheet-type design, possibly easier for power electronics interface; high dielectric constant material

Weaknesses: No samples available yet.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments: Industrial collaboration is a plus.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Samples have been sent to our industrial partner soon after we returned from the review at Oak Ridge.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Flux Weakening and CPSR Enhancement Techniques**

Presenter: **John McKeever** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: With the highest barrier being cost, the examination of designs using features such as concentrated windings is critical to achieving goals.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Teaming with UWM takes good advantage of outside resources.

Approach sufficiently innovative: Yes
If no, explain: Yes, but still could expand to use a combination of concentrated windings along with salient pole (IPM) rotor.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: The synchronous reluctance work was disappointing, but the concentrated winding work shows good promise.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Good focus on technologies which hold promise to be able to meet cost goals.

Weaknesses: High pole count, including fraction slot windings can result in additional losses, both core losses and potential for magnet losses in the rotor.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

This is definitely an area of increasing importance because the concentrated windings introduce concentrated flux fields that rotate within the stator causing increased stator eddy and hysteresis losses. Although the fundamental concentrated flux field rotates synchronously with the rotor, it contains harmonics that move relative to the rotor causing hysteresis and eddy currents in the rotor magnets and core material. Calculations of these losses have been made by Prof. Jahn's doctoral student, Aymen EL-Refaie for both the 6-kW motor with 36 slots and 30 poles, which has been fabricated and tested by the University of Wisconsin, Madison (UWM), and for the 55 kW version of the same motor proposed for use in an HEV traction drive. The method that Aymen used to make these loss estimates is discussed in Section 5.9 of his doctoral thesis, "High Speed Operation of Permanent Magnet Machines", University of Wisconsin-Madison 2005. In particular, the magnet losses are discussed in section 5.9.4. The three main sources of the eddy-current losses induced in the magnets are 1. winding space harmonics, 2. stator current time harmonics, and 3. space harmonics due to slotting effect. Aymen neglects the losses due to slotting effects for the bonded magnets that he used in the 6 kW design, but warns that this effect may be much larger for sintered rare earth magnets. In the March 2006 version of SPEED software used by ORNL to compare the motor designs with concentrated windings, magnet losses due to slotting effects is the only algorithm used. Aymen uses the method proposed by Atallah, Howe Mellor, and Stone entitled "Rotor Loss in Permanent -Magnet Brushless AC Machines, IEEE Transactions on Industry Applications, Vol. 36, No.6, Nov/Dec 2000.

HEV traction drives are being designed to operate at higher frequencies. As the speed increases, surface effects become increasingly important because current, which flows uniformly at low frequency, tried to flow closer to the surface. This increases the effective resistance, which reduces the losses. To help find an algorithm that will describe the surface effect at high speeds, ORNL requested in FY06 that UWM engage in research in this area. Magnet segmentation may be used to reduce magnet losses, which introduces interfaces that make it even more important to have a good method for describing surface effects to assure optimal design of the magnetization.

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 10*

Title: **Flux Weakening and CPSR Enhancement Techniques**

Presenter: **John McKeever** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Again, as my comment to Dr. Hsu, this is an ORNL strength to explore novel machine types and their applications to FreedomCAR. Understand program ends in FY06.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Technically sound approach with good outside collaboration with FSCW experts.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Solid report base and conference papers published. Does address all technical targets selected.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Novel machine with high CPSR.

Weaknesses: Issue/concern over core loss in rotor/stator.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments: Looking forward to project conclusion and comparison to dist. winding conventional machine.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

This is definitely an area of increasing importance because the concentrated windings introduce concentrated flux fields that rotate within the stator causing increased stator eddy and hysteresis losses. Although the fundamental concentrated flux field rotates synchronously with the rotor, it contains harmonics that move relative to the rotor causing hysteresis and eddy currents in the rotor magnets and core material. Calculations of these losses have been made by Prof. Jahn's doctoral student, Aymen EL-Refaie for both the 6-kW motor with 36 slots and 30 poles, which has been fabricated and tested by the University of Wisconsin, Madison (UWM), and for the 55 kW version of the same motor proposed for use in an HEV traction drive. The method that Aymen used to make these loss estimates is discussed in Section 5.9 of his doctoral thesis, "High Speed Operation of Permanent Magnet Machines", University of Wisconsin-Madison 2005. In particular, the magnet losses are discussed in section 5.9.4. The three main sources of the eddy-current losses induced in the magnets are 1. winding space harmonics, 2. stator current time harmonics, and 3. space harmonics due to slotting effect. Aymen neglects the losses due to slotting effects for the bonded magnets that he used in the 6 kW design, but warns that this effect may be much larger for sintered rare earth magnets. In the March 2006 version of SPEED software used by ORNL to compare the motor designs with concentrated windings, magnet losses due to slotting effects is the only algorithm used. Aymen uses the method proposed by Atallah, Howe Mellor, and Stone entitled "Rotor Loss in Permanent -Magnet Brushless AC Machines, IEEE Transactions on Industry Applications, Vol. 36,No.6, Nov/Dec 2000.

HEV traction drives are being designed to operate at higher frequencies. As the speed increases, surface effects become increasingly important because current, which flows uniformly at low frequency, tried to flow closer to the surface. This increases the effective resistance, which reduces the losses. To help find an algorithm that will describe the surface effect at high speeds, ORNL requested in FY06 that UWM engage in research in this area. Magnet segmentation may be used to reduce magnet losses, which introduces interfaces that make it even more important to have a good method for describing surface effects to assure optimal design of the magnetization.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 7***

Title: **Flux Weakening and CPSR Enhancement Techniques**

Presenter: **John McKeever** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain: Only part of project is useful.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: SR motor data does not address the fundamental NVH issues.

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Flux Weakening and CPSR Enhancement Techniques**

Presenter: **John McKeever** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Note: comments pertain primarily to flux weakening work. Work on CPSR would have gotten lower ratings overall. Flux weakening work is very relevant to needs of the FreedomCAR program and of OEMs to find more efficient, smaller, lighter, more cost effective motors.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Good solid engineering approach to the research. Strong engineering analysis preceded the build of the motor.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: One of the best projects in APEEM. Research stretches the state of knowledge about motors. Appear to have made the most progress among motor projects over the past year.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Solid engineering analysis preceded prototype build.

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM | ***Reviewer's Ability to Rate (1-10): 6***

Title: **Flux Weakening and CPSR Enhancement Techniques**

Presenter: **John McKeever** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 6***

Title: **Flux Weakening and CPSR Enhancement Techniques**

Presenter: **John McKeever** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Attacks all the key issues facing FreedomCAR. Also provides detailed work that can be utilized by OEMs.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Very complete. SR motor doesn't address the key issues on noise.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 10*

Title: **Flux Weakening and CPSR Enhancement Techniques**

Presenter: **John McKeever** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: High efficiency, high CPSR, etc. have been emphasized. Reluctance torque has been considered. Cost may not meet the target, but has been under consideration.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Design, analysis, modeling, simulation, and hardware models have been implemented to predict the performance.

Approach sufficiently innovative: No
If no, explain: It's a design improvement, not innovative project.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: A lower power hardware model has been tested to verify the performance. Different designs have been compared.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: A strong team with experience in PM machine design, modeling, analysis, simulation, and control.

Weaknesses: Not obvious.

Recommendations for Additions/Deletions to Project Scope: Verify the system performance with full-power model.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D **Reviewer's Ability to Rate (1-10): 2**

Title: **Flux Weakening and CPSR Enhancement Techniques**

Presenter: **John McKeever** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 4

Relevance Rating (1-4): **3**

Relevance Justification: Addresses many of the FreedomCAR pathways including optimize torque, increase CPSR, increase slot utilization, increase speed, reduce voltage, decrease active material & manufacturing to meet FreedomCAR goals.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Good collection of control data to focus on. Correct approaches for improvement.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Collected significant data on practical slot motors that showed promise. Conducted sufficient assessment to eliminate synchronous reluctance traction motors from further considerations.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Eliminated synchronous reluctance traction motors thus focusing further research.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 7*

Title: **Fully Integrated HEV Traction Motor Development Using Thermoelectrics**

Presenter: **Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **2**

Relevance Justification: It is not clear that there is a need to create these thermal islands, nor that the use of thermoelectrics are the best way to do it, if so.

Potential to Meet Technical Target: No

If no, explain: This is somewhat secondary, as it does not seem to address the main aspects of heat transfer for the application.

PI's Response to Relevance Questions/Comments: For the proposed application, i.e. an integration of silicon carbide power electronics with the traditional silicon based controller and polypropylene capacitors, there is a need for temperature control in the core of the integrated package.

Tight integration of the proposed components requires that some of the more temperature vulnerable components may be imbedded within a hot zone created by the very hot-running silicon carbide. Therefore, assuming that the integration of silicon carbide with standard circuitry is desired, then the application of TEs in this case is a good way to achieve that marriage with the benefit of high integration.

Approach Rating (1-4): **2**

Approach Justification: If thermoelectrics are a viable choice, it is not obvious from the results so far.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: The research and modeling that has been done so far with present-day thermoelectrics show that they are a viable solution for the proposed application. The project has been put on hold for the next year or so to evaluate emerging thin film thermoelectrics to see if they better supply the temperature gradient and heat flux that would enhance the results. The present-day thermoelectrics will function in this application's design, but at a lower overall delta temperature – at this level of performance, the silicon carbide benefits cannot be fully realized. This is why we are on hold until some of these parameters are improved.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: If thermoelectrics are a viable choice, it is not obvious from the results so far.

Accomplishments Sufficient: No

Significant Accomplishments During Year: The only material with substantial heat flux has an outlandish cost per surface area.

PI's Response to Technical Accomplishments Questions/Comments: By design, one can minimize the apparent surface area cost penalty, and utilize the much better cost measure of dollars per W/cm2. The present-day thin film TE devices (and the new thin-film technologies emerging on the market) on the surface appear to be much more expensive, but produce so much higher heat flux that thermo-mechanical designs can be made that capitalize on this very high heat flux. The real limitation to date is actually the upper temperature range for TEs. In addition, for thin film devices (which are based on semiconductor manufacturing techniques), at automobile manufacturing quantities, after another year or so of maturity, costs are expected to drop significantly.

Strengths:

Weaknesses: Seems focused on an area of minor returns for the overall program.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Fully Integrated HEV Traction Motor Development Using Thermoelectrics**

Presenter: **Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Original concept and very relevant to FreedomCAR. Today at vehicle sys level, it takes approx 1 W to remove 1 W of heat. Reaching for total air cooling is very valid.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: May want to consider two things--1) The thermal capacity of components on either side of the TE layer and, 2) System consideration of vehicle idle stop and key off energizing time of TE.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Excellent progress, especially the fully integrated AC drive.

Accomplishments Sufficient: Yes
Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Novel concept and good engineering motivation to provide thermal zones adequate to component protected.

Weaknesses: Experience with TEs

Recommendations for Additions/Deletions to Project Scope: Can ORNL do some simple heat flow experiments to evaluate the heat pumping characteristics of the TE's? This question of added power needed to remove a watt of heat must be answered.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: We have already performed some initial modeling using MatLab, basing the algorithms on manufacturers data. Efficiencies for TEs are known to be low, but coefficient of performance (COP) calculations have shown that layering the devices to improve delta T also dramatically improves the COP in a heat pumping mode.

One fundamental point to be made is if the application (combining silicon carbide with standard electronics) is a desirable technique, then a small additional loss (in the TE devices) to properly remove the heat is acceptable in order to gain the benefits of high temperature silicon carbide, use of air-cooling for the traction drive, and other possible benefits of the system concept.

It was originally intended to build laboratory models during this next fiscal year to validate both our thermal models and our TE layering/efficiency models. The project is on hold for the next year or so until some emerging technologies come to market, but laboratory prototyping and a validation endeavor is really the next goal.

Reviewer Affiliation: Industry **Reviewer's Ability to Rate (1-10): 7**

Title: **Fully Integrated HEV Traction Motor Development Using Thermoelectrics**

Presenter: **Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Though contingent on emerging technologies, this appears to be a high-benefit approach, if achieved. This could deliver a much simpler, air-cooled, and more reliable system. It also reduces cost of cables (there are none, if inverter and motor are more reliable system.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Creative and compact solution proposed.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Progress limited by development of thin film technology.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Simulation and design of multi-layer thermoelectric devices.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Innovative cooling and integration method.

Weaknesses: Would like to have seen a clearer explanation of the net benefit of this approach vs separate system baseline. The questions asked regarding power consumption vs. benefit show that this point was not well understood. (A presentation issue, not a project deficiency.)

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

At the time of presentation, the power consumption issues were still (and still are) being worked on. One of the slides presented showed a power flow chart which was based on a 5.6 kW motor system. The power consumption incurred in this design for the TE devices is around 70 watts, approximately an addition of 6% to the SYSTEM power losses, i.e. 73 W out of 1201 W. This is not 6% more loss of the system power, only 6% increase in the losses.

From the system level, the TEs present only 73/6700, or a 1% loss to the system. This one percent energy cost will potentially benefit the system by gaining the use of silicon carbide power devices, with high temperature operation, improved heat transfer, and potentially air cooling the entire traction drive. These improvements should manifest themselves as lower mass and volume of the traction drive, and thus some lower system cost.

The follow-on project to this one will delve more deeply into the system level power consumption issues, with much more complete thermal modeling of the power electronics and motor sections of the system. The complete models will validate TE payoffs with silicon carbide and air cooling designs.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 6***

Title: **Fully Integrated HEV Traction Motor Development Using Thermoelectrics**

Presenter: **Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 3

Relevance Rating (1-4): **2**

Relevance Justification: The cost of thermo-electric technology?

Potential to Meet Technical Target: No

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification:

Approach sufficiently innovative: No

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Fully Integrated HEV Traction Motor Development Using Thermoelectrics**

Presenter: **Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Research could prove to be very relevant to the mission of the FreedomCAR program and the needs of the OEMs for lower cost, compact, lightweight motors.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: A novel approach, but as DOE pointed out, may be ahead of its time. Agree with PI & DOE recommendations to delay further work until the technology catches up.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Good data and substantiation provided for work done during the year but progress inhibited by slow pace of technology development (unrelated to the work done by the PI). Initial reaction is that the approach may be an inefficient way to cool PE, but will withhold judgment until later when the technology catches up.

Accomplishments Sufficient: No

Significant Accomplishments During Year: See justification above.

PI's Response to Technical Accomplishments Questions/Comments: It needs to be re-iterated here that the intent of the TEs in this concept is not to cool the power electronics (which would be silicon carbide), but to protect the lower heat flux devices that are tightly packaged with the PEs. The real issues in this case are more the attainable delta T (to fully utilize the silicon carbide), and heat flux capability at those higher delta Ts.

Strengths: Novel approach.

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 7***

Title: **Fully Integrated HEV Traction Motor Development Using Thermoelectrics**

Presenter: **Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: Nice quick study and good decision to bookshelf this possible path for cooling. Thermoelectric capability gaps and cost are too great. Novel approach.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10):*** ***Reviewer did not provide a number.***

Title: **Fully Integrated HEV Traction Motor Development Using Thermoelectrics**

Presenter: **Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): Reviewer did not provide number.

Relevance Rating (1-4): **2**

Relevance Justification:

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: More because of maturity of technology.

Accomplishments Sufficient: none

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 4***

Title: **Fully Integrated HEV Traction Motor Development Using Thermoelectrics**

Presenter: ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Spot cooling is an excellent way to maximize performance at minimum cost and should be investigated if cost effective approaches can be identified.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: The use of Bi Te TEs for spot cooling of the hot areas permits active heat spreading eliminating localized hot spots from forming causing failure of power devices without requiring overcooling of non-hot areas. Layering approach to TE's shows promise.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good design and modeling of TE cooling layer approach. Limited in experimental validation & implementation of this approach by cost & availability of TE coolers.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: TE layer concept and design.

Weaknesses: Cost of the TE coolers.

Recommendations for Additions/Deletions to Project Scope: Agree this should be put on hold until cost effective, efficiency TE's are available. Perhaps need an internal program on TE Development.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 8*

Title: **Fully Integrated HEV Traction Motor Development Using Thermoelectrics**

Presenter: **Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification: Thermoelectric may find its place in very high power density design. For efficiency and cost points of view, it's not justifiable. It TE material is well developed, it can be naturally plugged into cooling application.

Potential to Meet Technical Target: No

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: Evaluating and testing TE for inverter cooling. The problem is that inverter does not represent real traction drive inverter.

Approach sufficiently innovative: No

If no, explain: This is only to evaluate TE application to traction motor and inverter, no novel application involved, no innovation approach in TE itself.

PI's Response to Approach Questions/Comments: The inverter design geometry being used here is very similar to one that is being built and tested at this time in our laboratory at a 60-70 kW output power level. The design in the subject application is built around a 6 kW system, but should be fully scalable to sizes into the >100 kW range. Again, the geometry for this design is already being proven in our laboratory in a direct cooling application. The only difference here is the cooling paths and temperature ranges, no real show stoppers are envisioned. The TE temperature control islands solve the "problems" or differences between the subject concept and the 65 kW inverter being tested in the lab at present.

It was never intended in this project to study fundamental TE design or application, only to utilize them in a packaging scheme that enables use of, for instance, silicon carbide high temperature power electronics, or air cooling of the traction drive. ORNL has applied for a patent for the packaging/cooling scheme, with the combination of silicon carbide with standard electronics. There are no known packaging designs that utilize TEs and silicon carbide in this way.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Some unproven models were developed. They need more convincible data to prove the model and thus applications.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Only pure modeling with conceptual layout and members that are not realistic.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Not obvious.

Weaknesses: No realistic system to work with. Low efficiency thermoelectric does not show any promise. Inverter to be coded is made up with an assumption that is not practical.

Recommendations for Additions/Deletions to Project Scope: Abandon the project.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: It had been intended that in the next fiscal year we would perform testing of the subcomponents individually and at a system prototype level. The research into TEs done early in this fiscal year showed the need to postpone this project for the next year or so, to wait/evaluate and see how the emerging thin-film TEs specifications improve. With that stated, though, the system concept could work with existing TEs, but at a lower system performance (not fully utilizing silicon carbide highest temperature capabilities).

We are postponing the project for the next year or so to evaluate how TE technologies improve (emerging products). We intend to monitor the technologies and assess how these improvements will benefit the system performance/efficiencies. It was stated during the presentation that the project would be put on hold (decided earlier this year) as a result of research discoveries and concept developments/requirements with the TE devices.

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 10*

Title: **Glass Dielectric Capacitors**

Presenter: **Mike Lanagan** ***Laboratory/Company:*** **PSU**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Glass ceramics show considerable promise. The issues will be in mechanical integrity and tangent delta at high temperature.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: I agree with the reviewer, the mechanical properties of thin glass substrates will be an issue in manufacturing and reliability of capacitors. We are exploring fabrication techniques that will minimize damage to the dielectric. Glass is a major material in automobiles (i.e. windows, headlamps, etc.) .

Approach Rating (1-4): **4**

Approach Justification: Having 2 glass technologies in runoff to FY07 down select is very good.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Need to how roadmap from 100 cm2 prototype fabrication capability to same sort of high volume linear process. Perhaps partners Corning and Schott can contribute to answer this.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: We have given these manufacturers prototype designs and cost targets. Schott Glass recently visited Penn State to discuss these designs. Corning will visit Penn State in October.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: I'd like to know if the proposed manufacturing processes result in any voiding or pitting in the glass dielectric that would end up magnifying electric field leading to corona leading to fracture.

Additional Comments: The capacitor industry does lack consistency in how cycle life is tested. There are no global standards. INRET's in France tests one way, other independent or state organizations do something different. As Tien said, maybe a workshop is in order to hash this out.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Surface finish is an issue for the glass-ceramics made at Penn State. The commercial flat-panel glass is very good quality and the manufacturing process has been optimized to avoid these types of defects at the production level.

In response to the statement, "The capacitor industry does lack consistency in how cycle life is tested. There are no global standards. INRET's in France tests one way, other independent or state organizations do something different. As Tien said, maybe a workshop is in order to hash this out." This is one of most important outcomes of the discussion. Perhaps we should have a workshop on how to quantify capacitor performance and reliability. The workshop should specifically address the EE Tech Team and DOE FreedomCAR concerns about capacitors. I volunteer to help put together this workshop next Spring in conjunction with our Center for Dielectric Studies meeting.

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 3*

Title: **Glass Dielectric Capacitors**

Presenter: **Mike Lanagan** ***Laboratory/Company:*** **PSU**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification: Clearly worthy S&T. Less obvious that this technology will impact HEV applications. Seems more suited for power supplies.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: Combination of university S&T and commercialization. The latter seems to be emphasis, but not clear how this approach will lead to clearly identified solution.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: The commercialization was emphasized in the presentation. The S&T follows from the justification for a scalable and low cost technology based on flat-panel displays.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Lots of activity. Progress may be moderated more by approach than enthusiasm. It's hard to see what are the clearly defined milestones. Again it appears to be worthy S&T, not specific engineering effort. Probably appropriate for this contractor.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: This is a particularly challenging research and development task. The approach is driven by the goal of finding a high temperature commercial material that will potentially be scaled-up. Progress is not moderated by the laboratory research which is relatively well defined. Progress must account for the time it takes to educate raw material suppliers such as Corning and Schott on the capacitor market and where their materials fit into hybrid vehicle technology. The education process involves testing the high temperature performance of glass, translating results to industry and DOE, and providing market data and DOE FreedomCAR cost goals to industry. Only industry has the manufacturing cost data to make a realistic assessment of the FreedomCAR cost goals.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM | ***Reviewer's Ability to Rate (1-10): 5***

Title: **Glass Dielectric Capacitors**

Presenter: **Mike Lanagan** | ***Laboratory/Company:*** **PSU**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **3**

Relevance Justification: Power electronics that meet FreedomCAR goals for cost, quality, durability and reliability are critical to the success of the FreedomCAR program and for the success of HEVs and FCEVs in the marketplace.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: Not enough information provided in the presentation to be able to determine if the approach is well designed or feasible. The slide about approach describes the need to "establish the processing science and technology needed..." but we never see any thing that leads one to determine if there is any processing science involved. Where is the description of the science? Where is the technology in this project or in this presentation?

Approach sufficiently innovative: No
If no, explain: Don't really know what is planned by the PI.

PI's Response to Approach Questions/Comments: Dielectric constant and loss were measured at Penn State on materials supplied by Corning and Schott. We have characterized a variety of samples and only the most promising material was shown at the APEEM review. The dielectric constant and loss show that these materials are very promising at high temperature and potentially can be used in capacitor applications.

Plans are to investigate graceful failure mechanisms in high temperature prototype capacitors. These capacitors will be small at first; however, the potential for scale-up is there. Glass materials are being mass produced for the consumer electronic market and there is some history of glass capacitor use in high- reliability military applications.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Difficult to assess technical accomplishments when none were reported. Need to see more technical details and results to be able to assess the project. Is the PI considering the unique & severe operating challenges of the automotive environment in his w

Accomplishments Sufficient: No

Significant Accomplishments During Year: No results reported to be able to assess the progress. This project has been ongoing since FY05. Why are we not seeing technical accomplishments?

PI's Response to Technical Accomplishments Questions/Comments: Yes, thermal, mechanical, and electrical stresses are being investigated. The results are compared with DOE FreedomCAR specifications for capacitors.

We have measured many dielectric materials and assessed the most promising materials in terms of scale-up. We have been collaborating with material manufacturers (Corning and Schott) and educating them on the potential of their materials for a new market (DC Bus capacitors). We have also been collaborating with capacitor manufacturers (TRS, Murata, and AVX) and interact with them on a weekly basis. In FY05 we began looking at glass ceramic materials and can supply result on these materials if there is interest. In FY06 we realized that scale-up will be an issue in glass ceramics and focused our attention on commercial flat-panel glass. We will continue our work on glass capacitors FY07.

Strengths: Difficult to tell if there are any. Great story about the glass industry but how is it relevant to technology development?

Weaknesses: PI spent far too much time and space in the presentation on background info. Left too little time for relevant tech. discussion. Only 3 of 20 slides had any semblance of technical content.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Recommendations for Additions/Deletions to Project Scope:

Additional Comments: Additional Comments on Weakness: So much time spent with unimportant information about the state of the glass industry, for example, left no time for substantive reports on the technical accomplishments of the project (assuming there were any). Disappointed that no time was allocated for a failure mechanism discussion.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Strengths: The main focus is on materials that can handle high electric field at high temperature which is essential for capacitor performance. We found that commercial glass has these properties.

Weaknesses: More information on our glass ceramic development can be forwarded to the reviewers if there is interest.

Additional Comments: We will provide discussion on our graceful failure mechanism in the annual report. Nineteen slides were used in the presentation. Three slides described specific capacitor requirements for DC bus capacitors and the gaps in commercial capacitors. Eleven slides were used to describe project milestones, collaboration, and future work. Only one slide (Slide #15) in the presentation was devoted to the state of the glass industry.

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 7*

Title: **Glass Dielectric Capacitors**

Presenter: **Mike Lanagan** ***Laboratory/Company:*** **PSU**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: Great potential for glass.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Show us as much data as possible to support the claims.

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: The major claim for this project is that glass materials have sufficient high temperature performance for DC bus capacitor applications. Slides 16 and 17 showed the data to support the claims.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Glass Dielectric Capacitors**

Presenter: **Mike Lanagan** ***Laboratory/Company:*** **PSU**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **3**

Relevance Justification: Data presented is insufficient to judge the merit of this project.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: The data were presented in slides 16 and 17. This is a general theme throughout this reviewer's comments. More data could be presented (Dielectric constant and loss data for a variety of materials). In addition, phase diagrams for the glass ceramic materials could be presented.

Approach Rating (1-4): **2**

Approach Justification: No data was provided. Need data to support presented material.

Approach sufficiently innovative: No
If no, explain: No data

PI's Response to Approach Questions/Comments: Dielectric constant and loss were measured at Penn State on materials supplied by Corning and Schott. These data were presented in slides 16 and 17. We have characterized a variety of samples and only the most promising material was shown. The dielectric constant and loss show that these materials are very promising at high temperature and potentially can be used in capacitor applications.

Data were reported in slides 16 and 17. More data on other materials can be supplied if there is

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: no comment

Significant Accomplishments During Year: Data is unavailable.

PI's Response to Technical Accomplishments Questions/Comments: Data were reported in slides 16 and 17.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM

Reviewer's Ability to Rate (1-10): Reviewer did not provide a number.

Title: **Glass Dielectric Capacitors**

Presenter: **Mike Lanagan** ***Laboratory/Company:*** **PSU**

Research is Important to FreedomCAR (1-10): Reviewer did not provide number.

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: Need data to support presented material.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 9***

Title: **Glass Dielectric Capacitors**

Presenter: **Mike Lanagan** ***Laboratory/Company:*** **PSU**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: Combination of polymer film & ceramic cap promises high volumetric efficiency with the temp stability of a ceramic and with a benign failure mode. This satisfies 3 essential DOE goals for a capacitor, which remain a critical limiting factor for development of coolant-free power modules.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Glass ceramics promise good reliability, power density, and temp stability. Leveraging off the flat panel drop lay glass industry is ingenious and shows great promise. Concern would be if the widespread us of flat panel glass will be able to lower price significantly to meet cost targets.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: Corning and Schott to determine if the raw materials are within the FreedomCAR cost target. In addition, Mike Lanagan and Jean Montemarano will contact ITW Paktron to understand their multilayer stacking process. Hopefully, the process can be adapted to glass sheets and brittle high-temperature polymers.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Development of commercial glass with good dielectric and reliability properties at 270°C is a major accomplishment in the path to a high temp, high reliability, high power density capacitor.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Integration of commercial flat panel glass into cap.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Potential to meet technical & cost goals through use of flat panel glass.

Weaknesses: No slides on benign failure mode in presentation. What is the status on that?

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: We have initiated work on electrodes on glass. There was no time to present our results at the review and the results will be added to the annual report. This is an area of focus for FY2007.

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 10*

Title: **Glass Dielectric Capacitors**

Presenter: **Mike Lanagan** ***Laboratory/Company:*** **PSU**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Low-cost high diversity capacitor is important. For this technology, temperature is emphasized. Cost is unknown. Failure mode could be a major problem.

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments: Low cost is important, which is the main reason to explore high-volume materials that are currently mass produced. The capacitor industry is driven by low-cost high-volume materials production. For example, polypropylene has uses in many consumer container products. The film capacitor industry leverages this high volume industry. PPS is a common polymer material for high-temperature film capacitors; however, there are no high volume industry applications so the cost will be high. The cost is a function of raw materials and manufacturing. We are working with Corning and Schott to determine the cost of prototype capacitors that are manufactured with commercial flat-panel display glass, which is a high volume industry.

Approach Rating (1-4): **3**

Approach Justification: No ripple current spec. or consideration in the design. Package is not considered for power electronics integration.

Approach sufficiently innovative: No
If no, explain:

PI's Response to Approach Questions/Comments: We can provide high field polarization data on glass ceramics which gives some idea of ripple current loss. Ripple current data were presented in a previous review and a comparison between the major capacitor technologies was made.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Only I µF, 600 V is available this year. It's 2,000 times less than the DOE spec?

Accomplishments Sufficient: No

Significant Accomplishments During Year: I tend to think the originally designed for low-voltage µ-computer application may not be directly scalable for high voltage high power. With only 1µF, 600 V sample available, it's impossible to show meaningful results.

PI's Response to Technical Accomplishments Questions/Comments: We are working with capacitor manufacturers to determine how to scale-up from 1 µF to 10 µF. In addition, we have visited the Air Force research lab at Wright Patterson Air Force Base. They are putting 50 capacitors in parallel and each capacitor is 5 µF, so the total capacitance is 250 µF. The important question to achieve 2000 µF: how to package smaller capacitors in parallel and what is the overall cost of doing this?

Prototype capacitors of 1 µF are very useful for understanding the fundamental high temperature performance of the materials. Higher capacitance values are not practical in an academic environment so we work with companies to scale-up. Our prototype capacitors operate above 600 V which exceeds the DOE FreedomCAR specification.

Strengths: High temperature material.

Weaknesses: Material could be brittle and not suitable for vehicle environment; very low capacitance; no ripple current capability indicated; no test plan either.

Recommendations for Additions/Deletions to Project Scope: Perhaps a waste of development for high power inverters.

Additional Comments: Interface to power electronics can be a problem; material strength can be a concern.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Glass is a major material in automobiles (i.e. windows, headlamps, etc.) We can set up a test facility to test ripple current.

A more specific comment on what is wasteful would be helpful. This is a multifaceted study in which involves designing equipment to characterize fundamental dielectric properties of capacitor materials, a novel HALT test for high temperature reliability test, collaboration with Industry, and addressing very specific capacitor requirements for DC bus capacitors.

Yes, the mechanical properties may be a concern. It is not clear what "interface to power electronics" means in this statement. Does this mean that the electrical contact from the capacitor to the power circuit is a problem or is it a philosophical question on a better link between materials and the performance and cost of a power electronics circuit?

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **High Temperature Inverter Development**

Presenter: **John Mookken** ***Laboratory/Company:*** **Semikron**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification: 105ºC inverter with silicon is a necessary effort, even if long-term, it won't be sufficient.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Technical approach was not designed for breakthrough, so none occurred. Solid engineering effort with appropriate emphasis on cost and near-term relevance. Perhaps conservative approach led to capacitor problem.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Technically successful. Focus on economics made final results short of goals, through no fault of contractor.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **High Temperature Inverter Development**

Presenter: **John Mookken** ***Laboratory/Company:*** **Semikron**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Project concluded.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: It's over.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Program ended without resolving economic issue of bus capacitors. Technical solution found but cost is high.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry | ***Reviewer's Ability to Rate (1-10): 5***

Title: **High Temperature Inverter Development**

Presenter: **John Mookken** | ***Laboratory/Company:*** **Semikron**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **3**

Relevance Justification: Project provides valuable information on packaging and associated reliability and cost. This is an important "reality-check" for other longer-term development projects.

Potential to Meet Technical Target: No

If no, explain: Capacitor cost is excessive for hi-temperature application.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Good plan, considering limitation of using only relatively mature technologies.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Great developments in die attachment technology, giving higher reliability. Summarized practical limitations of current and near-term technologies.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Demonstrated durability improvement in power cycling test using sintering die attachment. This has obvious benefits in improved system reliability.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Very practical approach, and good explanation of effect of hi-temp requirement on module cost.

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 6***

Title: **High Temperature Inverter Development**

Presenter: **John Mookken** ***Laboratory/Company:*** **Semikron**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: Higher temperature inverter ratings are key to reducing cost and increasing reliability.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: Starting with a known product and moving to higher temperature rating is a good approach to incremental improvements, but not innovative enough to make breakthroughs.

Approach sufficiently innovative: No
If no, explain: Just increasing temperature capability without real innovation.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Returning half of the funding, but giving up on finding something better than 3x cost capacitors (at high temperature) is not impressive.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Need to make real progress on capacitors.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Existing product starting point.

Weaknesses: Lack of accomplishment on capacitors.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry

Reviewer's Ability to Rate (1-10): 7

Title: **High Temperature Inverter Development**

Presenter: **John Mookken**

Laboratory/Company: **Semikron**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **2**

Relevance Justification: Came close to meeting current objectives, but goals changing. Technology stretch may not be great enough.

Potential to Meet Technical Target: No

If no, explain: Does not meet cost target.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Uses existing commercial technology. Where is the stretch?

Approach sufficiently innovative: No

If no, explain: OEMs today have similar technology available for sale.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Technology does not differentiated itself from existing commercial technology.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Does not meet cost target.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **High Temperature Inverter Development**

Presenter: **John Mookken** ***Laboratory/Company:*** **Semikron**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Power electronics that can meet the cost and temperature tolerance goals of the FreedomCAR program are critical to the success of the program and for OEMs to be able to offer HEVs that are affordable and can meet customer needs.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Practical approach to the research that considers manufacturability along with technical development.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Good results that allow the technology to be able to move quickly from the research arena to products. No significant technical barriers remain.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Semikron as an industry supplier brings a practical, businesslike perspective to the research, e.g., focusing on products that can reach production within a year.

Weaknesses: Unlikely to meet cost targets even without considering the high cost of capacitors.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **High Temperature Inverter Development**

Presenter: **John Mookken** ***Laboratory/Company:*** **Semikron**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 6***

Title: **High Temperature Inverter Development**

Presenter: **John Mookken** ***Laboratory/Company:*** **Semikron**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 8*

Title: **High Temperature Inverter Development**

Presenter: **John Mookken** ***Laboratory/Company:*** **Semikron**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 10***

Title: **High Temperature Inverter Development**

Presenter: **John Mookken** ***Laboratory/Company:*** **Semikron**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Integration allows substantial reduction in parasitic inductance and associated loss. Package allows high temperature operation.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Good integration but present significant problems in high temperature on capacitor and current sensor.

Approach sufficiently innovative: No
If no, explain: Yes on high integration. Need dramatic improvement on current sensor and capacitor.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Hardware development is completed. High temp packaging is very challenging.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: 1. High temperature packaging and operation. 2. Highly integrated module for parasitic reduction.

Weaknesses: 1. Sensor accuracy, possible problems for current mode control. 2. Still not practical for high temperature with capacitor problem.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 10***

Title: **High Temperature Inverter Development**

Presenter: **John Mookken** ***Laboratory/Company:*** **Semikron**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: Development of commercially available module for 105ºC coolant inlet temperature and 125ºC function temperature is a very important step on the road to FreedomCAR. However, the use of Si devices in a std inverter topology w/sintered die attachment is not high risk or long range.

Potential to Meet Technical Target: Yes

If no, explain: But didn't show the chart indicator where the R&D goals match the FreedomCAR goals.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: The approach of using Si die w/standard substrates and std. inverter topology is a very good approach to the successful production of a 125ºC inverter. The focus of reliability was very good.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: The low cost and high reliability of this module make its actual incorporation in a vehicle very likely. The demonstration of reliability of the sintered die attach was a very important advancement.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Completion of the module for incorporation in vehicle reliability. Demonstration of sintered die attach technology.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Low cost, high reliability, commercially ready module.

Weaknesses: Not high risk.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Identifying the Barriers and Approaches to Achieving High Temp Coolants**

Presenter: **Bob Staunton** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Project gives overview/oversight to existing thermal control projects.

Potential to Meet Technical Target: No

If no, explain: Strikes me as more of a coordinating project vs. development work.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Provides good overlap into power electronics and electric machines for thermal controls coordination.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Project concludes FY06. Provides good basis for future project starts.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Good rationale to have thermal controls provide liaison between machine and power electronics teams. Sort of a clearinghouse for thermal issues and coordination.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry   ***Reviewer's Ability to Rate (1-10): 8***

Title: **Identifying the Barriers and Approaches to Achieving High Temp Coolants**

Presenter: **Bob Staunton**   ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Though the goal is pretty broad, it is foundational to improving motors and inverters for HEV's/FCV's.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Good systematic approach.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 3***

Title: **Identifying the Barriers and Approaches to Achieving High Temp Coolants**

Presenter: **Bob Staunton** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: A focused study of this type is necessary for both tech S&T investment decision-making and, if results published in public domain, a valuable documentation for industrial policy formulation.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Technical approach adequate given that the analyst does not seem to be expert in this field himself. Overcome using literature and information from "experts." Weakness is getting data on proprietary components.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Difficulties with accessing proprietary data. May be holding back progress and may limit validity of final conclusions. Strongly suspect that "cost" estimate will be of limited value. Still, doing good job reporting the major benefit of project should be valuable contribution.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: System assessment with critical analysis. Report.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry   ***Reviewer's Ability to Rate (1-10): 8***

Title: **Identifying the Barriers and Approaches to Achieving High Temp Coolants**

Presenter: **Bob Staunton**   ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Understanding the barriers or hurdles is always an important step in problem solving.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: The impact of running the components at higher temperatures is not well accounted for in this simplified approach.

Approach sufficiently innovative: No
If no, explain: See additional comments.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: There is a need to more rigorously understand and account for the operation at higher temperatures, which was not done in this work.

Accomplishments Sufficient: No

Significant Accomplishments During Year: There is not a recognition of the negative impact of higher temperature on reliability, cost, efficiency, etc.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses: There is a real lack of engineering rigor in this work.

Recommendations for Additions/Deletions to Project Scope: In order not to mislead, the proper accounting for thermal effects needs to be made - rather than broad over simplifications.

Additional Comments: In regard to the motor cooling, it is overly simplistic to think that just a small increase in the heat exchanger will allow a 40°C increase in coolant temperature. Running magnets up to 220 (or even 180)°C is not realistic in terms of flux level, demag, and higher cost magnets.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: It was stated in the presentation that the heat exchanger modifications are a “start” and that other changes will have to be made. The fact is, there is no available motor of 55 kW maximum rating that is suitable for use with the high temperature coolant, as stated during the review. This project was intended to identify only design and cost barriers. ORNL agrees with your conclusions that more work needs to be done to realize high temperature operation of motors.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **Identifying the Barriers and Approaches to Achieving High Temp Coolants**

Presenter: **Bob Staunton** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **2**

Relevance Justification: Outlines issues but does not give solutions. If part or material is not available to meet FreedomCAR goals perhaps that is what the DOE should be working on.

Potential to Meet Technical Target: No

If no, explain: It's a restatement of what 105°C coolant means, but offers no solutions or path to solution.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: Points out issues but offers no solutions. Where is the technology?

Approach sufficiently innovative: No

If no, explain:

PI's Response to Approach Questions/Comments: This project was a barriers study, designed to identify the issues involved with high temperature operation of a traction drive. For instance, if a barrier is that no capacitor is available at the desired size and cost, that information was presented in the report. The project involved no in house R&D. We agree with your above comment that perhaps DOE should be working on the material availability problem.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: No technical solution proposed.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: See above comment.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Identifying the Barriers and Approaches to Achieving High Temp Coolants**

Presenter: **Bob Staunton** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **3**

Relevance Justification: Achieving high temperature capability is important to the achievement of practical and affordable power electronics for the FreedomCAR program and vehicle production.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: It is important to capture data that is known about thermal management for future reference and to help establish a baseline for future research.

Approach sufficiently innovative: No
If no, explain: Not necessarily innovative research but nevertheless necessary.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: More detail is needed to be of assistance at this time. Await final report to see how inclusive and comprehensive it is.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Might have expected more progress for a project that started early in the fiscal year.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: The data needs to be gathered in a form that is accessible for all to use for future reference.

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: We are in the process of issuing a comprehensive technical report that describes our barrier study in much detail. We are also reporting on the study, more briefly, in the ORNL FreedomCAR Annual Progress Report that will be issued in the next few months.

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **Identifying the Barriers and Approaches to Achieving High Temp Coolants**

Presenter: **Bob Staunton** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative:

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year: Lacking the details.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 7*

Title: **Identifying the Barriers and Approaches to Achieving High Temp Coolants**

Presenter: **Bob Staunton** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Involve specialists in getting more detail.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 8***

Title: **Identifying the Barriers and Approaches to Achieving High Temp Coolants**

Presenter: **Bob Staunton** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: Needs more detailed work to reach its project potential.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: More detailed work needed.

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 10***

Title: **Identifying the Barriers and Approaches to Achieving High Temp Coolants**

Presenter: **Bob Staunton** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Focus on assessing high temp electronics to permit the removal of the coolant loop promises significant cost and reliability advantages making it easier to meet DOE cost, size, weight, and reliability goals.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Focuses on capacitor as critical limitation which is good. Also focuses on 175°C IGBT as limitation which is really more of a packaging limitation. Provides good suggestions for improvement. Cost analysis is premature.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Capacitor & power electronics sections show significant data collection and analysis. Need to address specific limitations to motor operation at high coolant temperature & whether they are catastrophic or just lower performance during operation.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Confirms capacitor as critical limitation.

PI's Response to Technical Accomplishments Questions/Comments: The project report will soon be issued, In which this will be addressed quite well. Assuming that the designer uses appropriate materials (cooling oil, stator insulation, etc) there are no catastrophic issues unless the magnet critical temperature is surpassed and permanent demagnetization occurs. This depends on the peak temperature reached in the rotor, which must be determined by more detailed design analysis as stated in the presentation. Your phraseology of "just lower performance" may be underestimating the seriousness of the potential loss in performance (see final report).

Strengths: Identifies capacitor as critical limitation.

Weaknesses: Does not account for packaging which for high temp would be a significant factor in cost and performance. Cost analysis could be improved. It assumes no capacitors will be used in cooled system? (i.e. 7x$20/cap = $140 - initial cap cost $0) = $140. Assumes no price premium for high temp electronics. Many technical issues to address before cost analysis can be made.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 7***

Title: **Identifying the Barriers and Approaches to Achieving High Temp Coolants**

Presenter: **Bob Staunton** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: I believe that this type of study is very important for guiding/focusing research. The study has been done w/reasonable depth and breadth.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Overall, good. Without reading the report, it seems that some of the analysis was pretty simplistic, only identifying pretty obvious things.

Approach sufficiently innovative: Yes
If no, explain: Expect report to show more depth.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: It seems that there are many areas where the team could/should go into more depth, e.g.. demagnetization, heat exchangers. Do temperature distributions within components matter? It was good to compile all of this disparate information in one place.

Accomplishments Sufficient: Yes-but almost marginal.

Significant Accomplishments During Year: The entire report will be helpful, I think, in framing the future research.

PI's Response to Technical Accomplishments Questions/Comments: The study was scoped at a higher level as evidenced by its identification of several significant barriers for the motor and inverter systems. The project report will be issued soon in which more depth will be given to the issues you identify. Unfortunately the short time frame available to present the project at the review limits the detail that can be presented. Temperature distributions do matter and examples will be provided in the final report.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: More care in analysis of components, .i.e., temp. distributions worse than mean temps?

Additional Comments: Pace of presentation could be sped up.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 5***

Title: **Integrated DC/DC Converter for Multi-Voltage Bus Systems**

Presenter: **Gui-Jia Su** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: The need to be able to effectively and efficiently move between the various voltage levels of HEV's is important.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: It seems that the approach of trying to do both synchronous rectification and soft switching is adding complexity with unclear justification.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: The use of soft-switching and synchronous rectification is to reduce or eliminate switching and conduction losses, respectively. One good thing with our converter topology is that no extra components or complex control are needed to achieve soft-switching and synchronous rectification; the parasitic capacitance of the MOSFETs and the leakage inductance of the transformers are utilized.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: The 4 kW prototype has not yet been tested to its rated capacity.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Fully test 4 kW to its rating.

PI's Response to Technical Accomplishments Questions/Comments: The testing data shown at the review had been taken about a month before the review. Testing has been continued since then and is now successfully completed with power level all the way up to 4.3 kW and efficiency over 93%.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Need to test beyond the current 70% load on the 4 kW prototype.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 4***

Title: **Integrated DC/DC Converter for Multi-Voltage Bus Systems**

Presenter: **Gui-Jia Su** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: Stated goals of size and cost were not documented.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: What is the efficiency from 0 to 500 watts?
Why was a 2 kW building block chosen?
Could a lower power building block size be chosen to distribute the heat over a wider area possibly allowing for air cooling?

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: The efficiency from 0 to 500 W is 0 to 93%.

The reason for choosing a 2 kW building block is to utilize the design and experimental results of the 2 kW converter we have done in FY05. The initial choice of 2 kW rated power was from the requirement for a fuel cell dc-dc converter project under the PNGV program about eight years ago. We recognize that the choice of a 2 kW building block may not be an optimal choice.

Obviously, a lower power building block size can be used to distribute the heat over a wider area to facilitate heat removal, which is one of the benefits brought by the interleaved modular approach. It is, however, doubtful that this alone would be enough to allow for air cooling due to the limited operating temperatures of silicon chips and more importantly the quite larger thermal resistance between the chips and the heat sink. In addition, there are limits on the size and volume of the converter to be able to be installed in a vehicle.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: No cost comparisons shown.
No power density shown.
No size shown.
How do you justify the claim of reduced size and cost?

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Specific numbers are 1.1 kW/kg, 2.1 kW/L, and $60/kW, which exceed the 2015 specific power, power density, and the 2010 cost target.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **Integrated DC/DC Converter for Multi-Voltage Bus Systems**

Presenter: **Gui-Jia Su** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification: Very useful if split low voltage bus is required. How prevalent will that requirement be?

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: A triple voltage dc-dc converter will likely become indispensable in future multi-voltage system vehicles such as HEVs, Plug-in HEVs and Fuel Cell HEVs. As the automotive industry moves to drive-by-wire through the electrification of power steering, braking and suspension, the 42 V net will likely be used to handle these heavy loads because the existing 14V system cannot efficiently power those loads and with the higher voltage bus for traction drive it will be very difficult to meet the safety requiems and to cope with EMI issues by running high voltage wires throughout the vehicle. On the other hand, some of the other vehicle loads will be better stay at the 14 V net. While it is specially needed for fuel cell vehicles, which have no IC engines to assist those mechanisms, drive-by-wire technology has been employed in luxury vehicles. For example, Toyota RX400h SUV uses DC-DC converters to transform 201 V traction battery voltage to 14 V for onboard electronics and to 42 V for electric power steering. In an SUV, just the steering loads alone demand 42 V supply.

Approach Rating (1-4): **3**

Approach Justification: Main goal of increasing integration is achieved by approach. Inconsistent with respect to switching frequency. Does interleaving 2 kW blocks eliminate component reduction advantage?

Approach sufficiently innovative: yes
If no, explain:

PI's Response to Approach Questions/Comments: Need clarification on “Inconsistent with respect to switching frequency”. There is a tradeoff between the reduction in the size and volume of the passive components and the increase of switching and core losses by increasing the switching frequency. Obviously, the switching frequency needs to be optimized to achieve all the targets of cost, volume, weight and efficiency. One good thing is that the losses are reduced by the use of soft-switching and synchronous rectification in our converter.

As the power level increases, it will be very difficult to properly layout the components in a single block to minimize the resultant stray inductances of the interconnections. The stray inductances not only introduce additional losses but could cause the converter to not function properly. To facilitate heat removal, the heat generating components such as MOSFETs and transformers need to be spread over the heat sink, which will, however, increases the length of the interconnections and thus the stray inductances. The use of interleaved multiple modules not only solves this problem but brings additional benefits by decreasing the capacitor current and therefore the required capacitance and by providing easy power scaling capability to meet different power requirements without redesign of the whole converter. It certainly will increase the number of transformer and gate drivers but not the MOSFETs; the same number of MOSFETs will be needed for both single converter design and the interleaved multi-modular design for a given power rating. Another good feature with our topology is that the capacitor legs are shared among all the modules and their number does not increase.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Prototype looks impressive. Experimental work is always more difficult to achieve relevant progress. Don't know how much the progress addressed the most important barriers.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Construction of working prototype. Compact construction of prototype.

PI's Response to Technical Accomplishments Questions/Comments: Our converter will exceed the 2015 targets for Peak Power to Weight (kW/kg) and Peak Power to Volume (kW/L), and the 2010 cost target ($/kW).

Strengths:
Weaknesses:
Recommendations for Additions/Deletions to Project Scope:
Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 10***

Title: **Integrated DC/DC Converter for Multi-Voltage Bus Systems**

Presenter: **Gui-Jia Su** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: HEV, PHEV ,FCHV are all multi-voltage sys vehicles. Toyota RX400h SUV for example uses DC-DC converters to transform 201 V traction battery potential to 14 V for onboard electronics and to 42 V for electric power steering (EPS). In an SUV, the steering loads demand 42 V supply.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Too focused on steady state response/performance. Need 14 V continuous loading in the presence of 42V dynamic loading.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: Addressing dynamic responses is planned in the FY07 work plan as a major task.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Elimination of L-C on the 14 V bus helps reduce cost, wgt., vol., and is good trend. Needs assessment of all dynamic operating modes.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses: Continuation of existing program.

Recommendations for Additions/Deletions to Project Scope: Address all operating modes and power flow scenarios that will be encountered in a vehicle.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 5***

Title: **Integrated DC/DC Converter for Multi-Voltage Bus Systems**

Presenter: **Gui-Jia Su** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification: Not clear on what % system cost savings potential this approach would or could have. Also, not sure if 14 V-42 V bus is cost effective approach to begin with.

Potential to Meet Technical Target: Maybe

If no, explain: See above relevance justification above.

PI's Response to Relevance Questions/Comments: The projected cost is $60/kW, which exceeds the 2010 cost target of $75/kW.

A triple voltage dc-dc converter will likely become indispensable in future multi-voltage system vehicles such as HEVs, Plug-in HEVs and Fuel Cell HEVs. As the automotive industry moves to drive-by-wire through the electrification of power steering, braking and suspension, the 42V net will likely be needed to handle these heavy loads because the existing 14V system cannot efficiently power those loads and with the higher voltage bus for traction drive it will be very difficult to meet the safety requiems and to cope with EMI issues by running high voltage wires throughout the vehicle. On the other hand, some of the other vehicle loads will be better stay at the 14V net. While it is specially needed for fuel cell vehicles, which have no IC engines to assist those mechanisms, drive-by-wire technology has been employed in luxury vehicles. For instance, Toyota RX400h SUV uses dc-dc converters to transform the traction battery voltage to 14 V for onboard electronics and to 42 V for electric power steering. In an SUV, just the steering loads alone demand 42 V supply.

Approach Rating (1-4): **4**

Approach Justification: Given the project goals and definition (which I question the value of), the project is well-designed.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Good progress on simulation and circuit packaging. Demonstrated test confirmation of model predictions, showing feasibility.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: See accomplishment justification above.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 7***

Title: **Integrated DC/DC Converter for Multi-Voltage Bus Systems**

Presenter: **Gui-Jia Su** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **2**

Relevance Justification:

Potential to Meet Technical Target: No

If no, explain: Not significant enough savings to make a big impact.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: No

If no, explain: Does not appear to be a significant change of approach, just simple topology change.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 8*

Title: **Integrated DC/DC Converter for Multi-Voltage Bus Systems**

Presenter: **Gui-Jia Su** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **2**

Relevance Justification: Not long range/high risk R&D.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: No

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **Integrated DC/DC Converter for Multi-Voltage Bus Systems**

Presenter: **Gui-Jia Su** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification: Power electronics that can meet the cost and temperature tolerance goals of the FreedomCAR program are critical to the success of the program and for OEMs to be able to offer HEVs that are affordable and can meet customer needs. However there is some question whether there is enough technical stretch in this work to warrant federal funding. The work seems to be more evolutionary than revolutionary.

Potential to Meet Technical Target: No

If no, explain: May help achieve the targets but is it stretchy enough?

PI's Response to Relevance Questions/Comments: We certainly want power converters that can operate at high temperature and cost little. Unfortunately, nature is working against us. As all the studies show, with present and foreseeable future technologies, the cost of high temperature converters is prohibitively high. While we are hoping for silicon carbide switches, they are still far away from becoming commercially available at the voltage and current ratings necessary for HEVs and FCVs applications. They will also impose even higher cost burdens because SiC switches will likely be much more costly even at large quantities than Si devices due to the inherent higher processing cost of SiC materials at higher temperature and the high demanding of other better materials making up a SiC switch and packaging materials. It is therefore imperative to reduce the number of switches in power converters to reduce the system cost, which is the role of topology development. With the converter circuit being developed in this project, we are working exactly toward this end. In long term, our topology will be able to not only take the full advantages that SiC devices can bring with but also minimize the number of these costly devices.

To meet the FreedomCAR goals, projects are ongoing to cover every aspect of power electronics developments including components, converter topology and thermal management. We however need be aware that it is unreasonable to expect for every single project to address all the aspects. Topology development is no doubt one very important aspect and we certainly need good converter topologies that can contribute by themselves in cost and size reduction by reducing the number of components and can incorporate all the advances in better components and thermal management technology when they become available.

Approach Rating (1-4): **3**

Approach Justification: PI has proposed a design concept that can simplify the system but does not appear to be radical new technology.

Approach sufficiently innovative: No
If no, explain: See approach justification above.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Project is not aggressive enough in pursuit of long range, stretch technology that warrants national lab efforts. No real technical discovery is involved.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: The reviewer may not be able to appreciate it, but we believe a new converter topology that offers better efficiency, lower cost and more functions is indeed a real technical discovery. Furthermore, when applied with costly SiC switches in the future, the impacts and benefits will become much more significant.

Strengths: New design approach that may simplify the system.

Weaknesses: Question why ORNL is working on this technology. Are there any long range, stretch technical breakthroughs expected here that warrant federal funding? This project seems more like a developmental project, not the kind of R&D that stretches the technical knowledge base. PI did not plan his presentation time well. He spent far too much time on background information leaving too little time to discuss the results of the project and future plans.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

A triple voltage dc-dc converter will likely become indispensable in future multi-voltage system vehicles such as HEVs, Plug-in HEVs and Fuel Cell HEVs. As the automotive industry moves to the ultimate goals of drive-by-wire for vehicle control through the electrification of power steering, braking and suspension, a 42 V net will likely be needed to handle these heavy loads because the existing 14V system cannot efficiently power those loads and with the higher voltage bus for traction drive it will be very difficult to meet the safety requiems and to cope with EMI issues by running high voltage wires throughout the vehicle. While this is specially needed for fuel cell vehicles, which have no IC engines to assist those mechanisms, drive-by-wire technology has already been employed in luxury vehicles. For example, Toyota RX400h SUV uses dc-dc converters to transform the traction battery voltage to 14 V for onboard electronics and to 42 V for electric power steering. In an SUV, just the steering loads alone demand 42 V supply.

The likely choice of future power devices for automotive applications will be SiC switches. These will be much more costly, even in large quantities, than Si devices. This is likely to be primarily due to the inherent higher processing cost of SiC materials and the need for higher temperature packaging materials. It is therefore imperative to reduce the number of SiC switches in power converters to reduce the system cost. With the converter topology being developed in this project, we are working toward this end. In the long term, our topology will be able to not only enable multi-voltage systems needed in future vehicles while taking the full advantages of SiC devices but also minimize the number of these costly devices, thus providing significant impact of future SiC based converters.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 6***

Title: **Integrated DC/DC Converter for Multi-Voltage Bus Systems**

Presenter: **Gui-Jia Su** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification: This is not a long-range, high risk R&D project. It is an engineering project.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain: Not very innovative.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 10*

Title: **Integrated DC/DC Converter for Multi-Voltage Bus Systems**

Presenter: **Gui-Jia Su** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Possible reduction on component counts by integrating multiple converters.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Improve efficiency with multi-phase interleave. Elimination of inductor may reduce component count, but will have problems of (1) startup, (2) non-optimum efficiency.

Approach sufficiently innovative: No

If no, explain: Idea is ok but energy conversion cannot be voltage to voltage. The middle stage should have energy stored in current form. The approach imposes a lot of stress into middle stage transformer.

PI's Response to Approach Questions/Comments:

It is certainly impractical to transfer power at high power levels directly between voltage sources such as with the switched capacitor dc-dc converters, which do not use magnetics, but it is only feasible at power levels below a few watts. In addition, the requirement of galvanic isolation demands a transformer based converter. Our topology, however, doesn't violate theses rules. First, the 14 V bus is derived directly from the 42 V bus by a capacitor voltage divider network not through switching operations. Second, because the leakage inductances of the transformers between the 42 V and H.V. busses is used as energy storage elements, it does not lead to a direct voltage source to voltage source power conversion.

For a given bus voltage, V42V, and switching frequency, fsw, varying the duty ratio, d, will change the peak flux linkage, Ψpeak, of the transformer but will not introduce a dc bias. This is due to the fact that the positive transformer terminal voltage, Vp, is (1-d) xV42V at a interval of tP= d/fsw, and the negative transformer terminal voltage, VN, is dV42V but at a interval of tN=(1-d)/fsw, leading to the same product of voltxsecond of d(1-d)V42V/fsw over the positive cycle and negative cycle. Further, operating at a duty ratio other than the usually employed 50% will decrease the peak flux linkage and thereby transformer stress. The peak flux linkage is determined by Ψpeak = ±d(1-d)V42V/(2fsw). At d = 50 %, Ψpeak = ±V42V/(8fsw) while at d = 1/3 for our converter, the peak flux linkage is reduced to Ψpeak = ±V42V/(9fsw) and thus a smaller transformer core can be used at the same switching frequency and number of turns.

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Prototype has been built to show some results. Packaging is significantly improved over past years.

Accomplishments Sufficient:

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Significant progress from previous year's effort. Efficiency is improved. Package is also improved.

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Is 42 V still considered by auto industries? Most of contacts and collaborators expressed to me that they are giving up 42 V camp.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

As the automotive industry moves to drive-by-wire through the electrification of power steering, braking and suspension, the 42 V net will likely be needed to handle these heavy loads because the existing 14 V system cannot efficiently power those loads and with the higher voltage bus for traction drive it will be very difficult to meet the safety requirements and to cope with EMI issues by running high voltage wires throughout the vehicle. While this is specially needed for fuel cell vehicles, which have no IC engines to assist those mechanisms, drive-by-wire technology has already been employed in luxury vehicles. For instance, Toyota RX400h SUV uses dc-dc converters to transform the traction battery voltage to 14 V for onboard electronics and to 42 V for electric power steering. In an SUV, just the steering loads alone demand 42 V supply.

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 4***

Title: **Integrated DC/DC Converter for Multi-Voltage Bus Systems**

Presenter: **Gui-Jia Su** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification: Project R&D goals significantly exceed the FreedomCAR goals. The elimination of one converter & transformer promises significant reductions in system cost, size and volume but combining two converters into one with reasonable efficiency and losses is a challenge.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Good topology for demonstrating power scaling capability.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good simulation, design & development of prototypes with actual test validation of the simulation.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Prototypes developed & tested to validate approach.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 8***

Title: **Interior Permanent Magnet Reluctance Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Good potential to reduce system cost, and reduce core loss.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Creative approach, exploiting various concepts, e.g., unsymmetric surface shaping, axial field, etc. Concepts are simple enough to implement and be practical. Axial flux allowed thick bridges to withstand high rpm.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Demonstrated advantages of approach compared to Prius, using relevant FreedomCAR metrics. I have some concern that the list of metrics may be incomplete (see comments on weaknesses).

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Demonstration of an alternative to using boost DC-DC converter with superior power density, compared to Prius technology.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Very creative and still practical.

Weaknesses: Not sure about considerations such as demagnetization, torque ripple, or torque requirement. Were these considered -- if so, what assumptions were made? These factors are not easily dealt with "after-the-fact" of optimizing the design without these constraints. Also, not what thermal limits were used in study.

Recommendations for Additions/Deletions to Project Scope: I recommend using the above constraints in design optimizations, comparisons, and reporting metrics.

Additional Comments: Nice work.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Due to the innovative method of cooling the motor demagnetization, as well as thermal limitations should not be an issue. Torque ripple can be calculated based on detailed 3D flux distribution simulation. At the initial simulation stage, we considered different dimensional components. The detailed losses and harmonic torque will be investigated through both simulation results and experimental tests conducted next year. All of the FreedomCAR design constraints were taken into consideration during the design and simulation of this project.

The design for the 16K RPM motor not only optimizes torque capability but also incorporates the ability to weaken the air gap flux density. The need for low core losses across a wide range of speed was also addressed in this design.

This motor is still in the development stage. Validation data will be available after initial testing is completed this year. Please see our Annual report for additional information.

Our motor is intentionally designed for low air gap flux density at high speeds with no field excitation current applied This solves the high core loss problem of the existing Prius/Highlander-type, high-PM-flux-density, high-speed motors which are plagued with both high core and high d-axis current losses necessary for field weakening.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 8***

Initial test results show: (1) The back emf can be controlled effectively through the external field excitation current with a range of current from zero to 5 amps, thus negating the necessity of using a boost converter to overcome high back emf. The air gap flux density can change up to 2.5 times at a given speed. This enables the motor to have all the advantages of both the existing strong PM reluctance (i.e., high power density, high back emf at high speed, high core loss) and the weak PM reluctance (i.e., low power density, low back emf, lower core loss) motors without their disadvantages. The additional circuitry necessary to supply the excitation current to the coils should cost less than ten dollars in production quantities. (2) The core and friction loss tests conducted show the benefits of lower air-gap flux density. For example, at 5000 rpm the core and friction loss is 200 W with zero field excitation as compared with 600W at high field excitation for a high air gap flux density.

This inherently low air gap flux density motor design enables significantly lower core losses at high speeds. Yet at low speeds when high torque is needed the ability to enhance the field can dramatically boost the torque. The excitation coils coupled with this low air gap flux design enables the motor to be controlled or 'fine tuned' to operate in its highest efficiency areas across the torque/speed curve.
Based on the experience of building the prototype at ORNL it is anticipated that, the motor will not present any complicated manufacturing issues. This is certainly a concern with any design undertaken at ORNL. As design progresses and transitions to industry an industrial partner will be brought in to assist us in identifying and resolving these issues.

No issues with added gearbox complexity are expected. We do not foresee a more complex gearbox than the planetary gearbox that is currently used by some of the automotive manufacturers.

The prototype motor can be further reduced in mass and volume by redesigning the interface between the excitation coils and the motor housing. This improvement will reduce the cost to manufacture the motor by the elimination of some machining steps as well as raw materials.

The comparison of mass and size gives a foundation for a cost comparison with the Prius motor (see chart below).

	Prius	**ORNL**
Speed_	6000 rpm	16,000 rpm
Stator Lam. OD_	10.6”	same
Rotor OD_	6.375”	same
Core length_	3.3”	1.88”
Bearing to Bearing outer face_	7.75”	7.45”
Magnet Weight lbs_	2.75	2.57
Estimated field adj. ratio_	none	2.5
Rating_	33/50 kW	same
Boost converter_	yes	No
High speed core loss_	high	low

In addition to the low loss performance improvement, this motor design eliminates the requirement for a boost converter, which not only simplifies the power electronics but enables a cost savings in the total drive system. The extra excitation coils and cores are made of copper wires and mild steel. Their total cost is compensated by the savings realized by a shorter stator core (1.875” as compared with the 3.3” of Prius) and shorter stator winding. The low-current (5 amps, maximum) control of the field excitation costs is minimal due to the low-current components required. This motor design enables a better performance motor with system cost savings.

Additionally, if used in a vehicle architecture requiring a boost converter this motor can produce 250 kW output at 16,000 rpm. This significantly widens the possible applications for this type of motor.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Interior Permanent Magnet Reluctance Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: Tradeoffs to optimize efficiency - not just at one operating point - but rather across the range of loads and speeds is an important aspect of performance.

Potential to Meet Technical Target: No

If no, explain: Motor complexity appears to not be on a path to meet cost targets.

PI's Response to Relevance Questions/Comments: See comments below.

Approach Rating (1-4): **3**

Approach Justification: Innovation from a technical standpoint is good. However, the design does not appear to have good cost capability. This may be ok for now, as disruptive technologies sometimes do not initially appear feasible. However, the typical scenario for disruptive technology is for the cost to look good, but the performance to initially appear to be inferior.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: The Prius comparison is not valid, in that there is the opportunity to weaken the field through the use of negative d-axis current. This is similar to the field weakening proposed in Hsu's method.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Until the hardware is built, the theory has not been proven, so I would defer judging the progress to this point.

PI's Response to Technical Accomplishments Questions/Comments:

The use of negative D-axis stator AC winding current is not as effective as the brushless field excitation. The reason is the negative D-axis current would come from the inverter which increases the loading of the inverter. Also, it would heat up the AC winding. The number of turns of the AC winding is very low compared to the number of turns of the DC excitation coil. Therefore, in order to produce sufficient ampere turns to adjust the field strength, the DC excitation coil requires a very small current as compared to the higher D-axes current.

The initial test shows we have a very effective field adjustment capability. We expect the hardware prototype to perform similarly.

Strengths: Highly innovative in regard to machine geometry.

Weaknesses: Does not keep the design simple from a manufacturing standpoint, so cost will be a challenge. Also, does not appear to fully recognize the ability to field weaken the Prius style IPM machine.

Recommendations for Additions/Deletions to Project Scope: More completely characterize and take into account the complexity of the field excitation system. This is both from a cost and reliability standpoint.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

The excitation system is not complicated. We do not foresee a manufacturing problem based on our experience of building the prototype. Additional cost from the system will be negligible as compared to the additional functionality the motor can provide, i.e. lower core loss and eliminating the DC/DC boost converter.

Our motor is intentionally designed for low air gap flux density at high speeds with no field excitation current applied This solves the high core loss problem of the existing Prius/Highlander-type, high-PM-flux-density, high-speed motors

Initial test results show: (1) The back emf can be controlled effectively through the external field excitation current with a range of current from zero to 5 amps, thus negating the necessity of using a boost converter to

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 9*

overcome high back emf. The air gap flux density can change up to 2.5 times at a given speed. This enables the motor to have all the advantages of both the existing strong PM reluctance (i.e., high power density, high back emf at high speed, high core loss) and the weak PM reluctance (i.e., low power density, low back emf, lower core loss) motors without their disadvantages. The additional circuitry necessary to supply the excitation current to the coils should cost less than ten dollars in production quantities. (2) The core and friction loss tests conducted show the benefits of lower air-gap flux density. For example, at 5000 rpm the core and friction loss is 200 W with zero field excitation as compared with 600 W at high field excitation for a high air gap flux density.

This inherently low air gap flux density motor design enables significantly lower core losses at high speeds. Yet at low speeds when high torque is needed the ability to enhance the field can dramatically boost the torque. The excitation coils coupled with this low air gap flux design enables the motor to be controlled or 'fine tuned' to operate in its highest efficiency areas across the torque/speed curve.
The design for the 16K RPM motor not only optimizes torque capability but also incorporates the ability to weaken the air gap flux density. The need for low core losses across a wide range of speed was also addressed in this design.

This design maximizes the thickness of the rotor punching bridges (material between the magnet slots in the rotor to satisfy the mechanical stress requirements at the high speeds required of this machine. More leakage flux produced by the permanent magnets (PM) can go through these bridges so the air gap flux density produced by the PMs will be lower than other similar IPM machines like the lower-speed Prius motor.

This motor is still in the development stage. Validation data will be available after initial testing is completed this year. Please see our Annual report for additional information.

Based on the experience of building the prototype at ORNL it is anticipated that, the motor will not present any complicated manufacturing issues. This is certainly a concern with any design undertaken at ORNL. As design progresses and transitions to industry an industrial partner will be brought in to assist us in identifying and resolving these issues.
No issues with added gearbox complexity are expected. We do not foresee a more complex gearbox than the planetary gearbox that is currently used by some of the automotive manufacturers

The prototype motor can be further reduced in mass and volume by redesigning the interface between the excitation coils and the motor housing. This improvement will reduce the cost to manufacture the motor by the elimination of some machining steps as well as raw materials.

The comparison of mass and size gives a foundation for a cost comparison with the Prius motor (see chart below).

	Prius	**ORNL**
Speed_	6000 rpm	16,000 rpm
Stator Lam. OD_	10.6"	same
Rotor OD_	6.375"	same
Core length_	3.3"	1.88"
Bearing to Bearing outer face_	7.75"	7.45"
Magnet Weight lbs_	2.75	2.57
Estimated field adj. ratio_	none	2.5
Rating_	33/50 kW	same
Boost converter_	yes	No
High speed core loss_	high	low

In addition to the low loss performance improvement, this motor design eliminates the requirement for a boost converter, which not only simplifies the power electronics but enables a cost savings in the total drive system. The extra excitation coils and cores are made of copper wires and mild steel. Their total cost is compensated by the savings realized by a shorter stator core (1.875" as compared with the 3.3" of Prius) and shorter stator winding. The low-current (5 amps, maximum) control of the field excitation costs is minimal due to the low-current components required. This motor design enables a better performance motor with system cost savings.

Additionally, if used in a vehicle architecture requiring a boost converter this motor can produce 250 kW output at 16,000 rpm. This significantly widens the possible applications for this type of motor.

Reviewer Affiliation: Industry | ***Reviewer's Ability to Rate (1-10): 10***

Title: **Interior Permanent Magnet Reluctance Machines**

Presenter: **John Hsu** | ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Good focus on fundamental needs of future traction drive systems. High speed operation and how to minimize core loss. Consideration given to mating with energy storage side and to inverter.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: The non-symmetric air gap and rotation direction bias may be problematic. For example, as traction motor in a power split under reverse (back-up) a grade or in generator (4 quad op).

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: This has been considered in the design. In the forward direction the reluctance torque is enhanced through the field excitation coils. In the backward (reverse) direction reluctance torque is reduced through the field excitation coils. The backward (reverse) torque is compensated by the use of a higher current in a shorter time frame.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Modeling and simulation to date are on schedule and prototype fab is on track. I question the 16K rpm machine overall torque/kg PM as baseline Prius torque/kg PM. The 6K rpm project with side magnets - same concern.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: The design for the 16K RPM motor not only considers the torque capability but also considers the requirement for a weak air gap flux density. The need for low core loss across a wide range of excitation was also addressed. Further, the rotor punching bridges (material between the magnet slots in the rotor) are much thicker due to the mechanical stress requirements at high speeds. More leakage flux produced by the Permanent Magnet (PM) would go through these bridges so the air gap flux density produced by the PM would be lower than the low speed Prius motor. For the reasons presented above our torque/Kg PM would be lower.

Strengths: ORNL pushes the envelope in machine concepts and this is extremely important in the mature electric machines business. Using Prius machine as baseline adds credibility.

Weaknesses: Lacks prototype validation at this stage.

Recommendations for Additions/Deletions to Project Scope: Concern over BFE mass, volume, cost factors--not to mention field excitation losses on composite efficiency, especially at high speeds.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: This motor is still in the development stage. Validation data will be available after initial testing is completed. Please see the Annual report for additional information.

The prototype motor can be further reduced in mass and volume by redesigning the interface between the excitation coils and the motor housing. This improvement will reduce the cost to manufacture the motor by the elimination of some machining steps as well as raw materials.

The comparison of mass and size gives a foundation for a cost comparison with the Prius motor (see chart below).

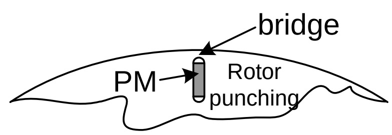
Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 10***

	Prius	**ORNL**
Speed_	6000 rpm	16,000 rpm
Stator Lam. OD_	10.6”	same
Rotor OD_	6.375”	same
Core length_	3.3”	1.88”
Bearing to Bearing outer face_	7.75”	7.45”
Magnet Weight lbs_	2.75	2.57
Estimated field adj. ratio_	none	2.5
Rating_	33/50 kW	same
Boost converter_	yes	No
High speed core loss_	high	low

In addition to the low loss performance improvement, this motor design eliminates the requirement for a boost converter, which not only simplifies the power electronics but enables a cost savings in the total drive system. The extra excitation coils and cores are made of copper wires and mild steel. Their total cost is compensated by the savings realized by a shorter stator core (1.875” as compared with the 3.3” of Prius) and shorter stator winding. The low-current (5 amps, maximum) control of the field excitation costs is minimal due to the low-current components required. This motor design enables a better performance motor with system cost savings.

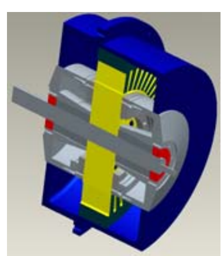
The design for the 16K RPM motor not only optimizes torque capability but also incorporates the ability to weaken the air gap flux density. The need for low core losses across a wide range of speed was also addressed in this design.

This design maximizes the thickness of the rotor punching bridges (material between the magnet slots in the Rotor (see sketch below) to satisfy the mechanical stress requirements at the high speeds required of this machine. More leakage flux produced by the permanent magnets (PM) can go through these bridges so the air gap flux density produced by the PM’s will be lower than other similar IPM machines like the lower-speed Prius motor.



This motor is still in the development stage. Validation data will be available after initial testing is completed this year. Please see our Annual report for additional information.

Our motor is intentionally designed for low air gap flux density at high speeds with no field excitation current applied This solves the high core loss problem of the existing Prius/Highlander-type, high-PM-flux-density, high-speed motors which are plagued with both high core and high d-axis current losses necessary for field weakening.



16,000 rpm Machine

Initial test results show: (1) The back emf can be controlled effectively through the external field excitation current with a range of current from zero to 5 amps, thus negating the necessity of using a boost converter to overcome high back emf. The air gap flux density can change up to 2.5 times at a given speed. This enables the motor to have all the advantages of both the existing strong PM reluctance (i.e., high power density, high back emf at high speed, high core loss) and the weak PM reluctance (i.e., low power density, low back emf, lower core loss) motors without their disadvantages. The additional circuitry necessary to supply the excitation current to the coils should cost less than ten dollars in production quantities. (2) The core and friction loss tests conducted show the benefits of lower air-gap flux density. For example, at 5000 rpm the core and friction loss is 200 W with zero field excitation as compared with 600W at high field excitation for a high air gap flux density.

This inherently low air gap flux density motor design enables significantly lower core losses at high speeds. Yet at low speeds when high torque is needed the ability to enhance the field can dramatically boost the torque. The excitation coils coupled with this low air gap flux design enables the motor to be controlled or ‘fine tuned’ to operate in its highest efficiency areas across the torque/speed curve.

Based on the experience of building the prototype at ORNL it is anticipated that, the motor will not present any

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 10***

complicated manufacturing issues. This is certainly a concern with any design undertaken at ORNL. As design progresses and transitions to industry an industrial partner will be brought in to assist us in identifying and resolving these issues.

No issues with added gearbox complexity are expected. We do not foresee a more complex gearbox than the planetary gearbox that is currently used by some of the automotive manufacturers.

Additionally, if used in a vehicle architecture requiring a boost converter this motor can produce 250 kW output at 16,000 rpm. This significantly widens the possible applications for this type of motor.

Reviewer Affiliation: OEM **Reviewer's Ability to Rate (1-10): 8**

Title: **Interior Permanent Magnet Reluctance Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification: The presenter did not provide enough design or simulation data to evaluate the motor performance.

Potential to Meet Technical Target: No

If no, explain: Not enough data to judge accurately.

PI's Response to Relevance Questions/Comments: This motor is still in the development stage. Validation data will be available after initial testing is completed this year. Please see our Annual report for additional information.

Approach Rating (1-4): **2**

Approach Justification: Not enough data.

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Insufficient data.

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

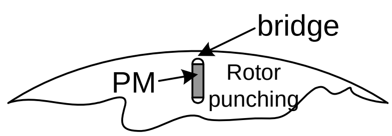
Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

The design for the 16K RPM motor not only optimizes torque capability but also incorporates the ability to weaken the air gap flux density. The need for low core losses across a wide range of speed was also addressed in this design.

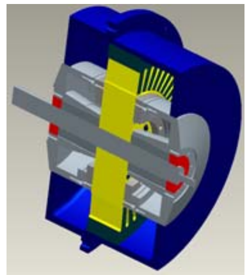
This design maximizes the thickness of the rotor punching bridges (material between the magnet slots in the Rotor (see below) to satisfy the mechanical stress requirements at the high speeds required of this machine. More leakage flux produced by the permanent magnets (PM) can go through these bridges so the air gap flux density produced by the PMs will be lower than other similar IPM machines like the lower-speed Prius motor.



This motor is still in the development stage. Validation data will be available after initial testing is completed this year. Please see our Annual report for additional information.

Our motor is intentionally designed for low air gap flux density at high speeds with no field excitation current applied This solves the high core loss problem of the existing Prius/Highlander-type, high-PM-flux-density, high-speed motors which are plagued with both high core and high d-axis current losses necessary for field weakening.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 8***



16,000 rpm Machine

In addition to the low loss performance improvement, this motor design eliminates the requirement for a boost converter, which not only simplifies the power electronics but enables a cost savings in the total drive system. The extra excitation coils and cores are made of copper wires and mild steel. Their total cost is compensated by the savings realized by a shorter stator core (1.875" as compared with the 3.3" of Prius) and shorter stator winding. The low-current (5 amps, maximum) control of the field excitation costs is minimal due to the low-current components required. This motor design enables a better performance motor with system cost savings.

Additionally, if used in a vehicle architecture requiring a boost converter this motor can produce 250 kW output at 16,000 rpm. This significantly widens the possible applications for this type of motor.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Interior Permanent Magnet Reluctance Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **2**

Relevance Justification: While electrical machines are critical to the success of the FreedomCAR program the 16000 rpm machine seems unnecessarily complicated and potentially expensive to be viable for auto OEM applications. Design may prove to be very complicated to manufacture.

Potential to Meet Technical Target: No

If no, explain: see previous comment

PI's Response to Relevance Questions/Comments: Based on the experience of building the prototype, the motor is not complicated for manufacturing. This is certainly an issue with any design we undertake at ORNL. As designs move further along in the development/transition to industry an industrial partner will be brought in to work on these issues with us.

Approach Rating (1-4): **3**

Approach Justification: The design is innovative and creative which is commendable. Innovative design approaches are to be encouraged to provide breakthrough improvements. However it is unclear if there was any extensive engineering analysis done before the design and prototype work was begun. The presentation does not share any such background information.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: Analysis done before the design and prototype work was begun.
There was extensive engineering work done on both the electro-magnetic and mechanical computations before the prototype was produced. Multiple designs and iterations were analyzed at the electromagnetic and mechanical level before a final design was decided upon.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: It is very difficult to evaluate this project because so little data is provided by the PI. Need to see more data to be able to evaluate properly.

Accomplishments Sufficient: No

Significant Accomplishments During Year: As mentioned above it would be nice if the PI would share more data.

PI's Response to Technical Accomplishments Questions/Comments: More data will be available in the Annual Report. As this project moves forward more test data will become available for comparison to the simulated results. This motor is still in the development stage. Validation data will be available after initial testing is completed. Please see the Annual report for additional information.

Strengths: Innovative design approaches to major program challenges

Weaknesses: Lack of detailed results and data shared by PI. PI needs to communicate more information in the presentation. Need to better understand what engineering analysis took place before the designs were moved into the prototype stage of project.

Recommendations for Additions/Deletions to Project Scope: Scale back or cancel unless proven to be able to be a viable, feasible, and affordable design. Need to consider systems implications. Is the design shifting cost, weight, package, etc. to other systems?

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Based on the experience of building the prototype at ORNL it is anticipated that, the motor will not present any complicated manufacturing issues. This is certainly a concern with any design undertaken at ORNL. As design progresses and transitions to industry an industrial partner will be brought in to assist us in identifying and resolving these issues.

No issues with added gearbox complexity are expected. We do not foresee a more complex gearbox than the planetary gearbox that is currently used by some of the automotive manufacturers

The prototype motor can be further reduced in mass and volume by redesigning the interface between the excitation coils and the motor housing. This improvement will reduce the cost to manufacture the motor by the elimination of some machining steps as well as raw materials.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

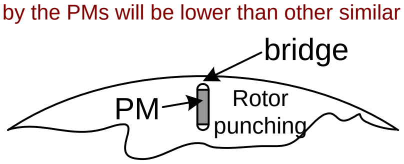
The comparison of mass and size gives a foundation for a cost comparison with the Prius motor (see chart below).

	Prius	ORNL
Speed_	6000 rpm	16,000 rpm
Stator Lam. OD_	10.6"	same
Rotor OD_	6.375"	same
Core length_	3.3"	1.88"
Bearing to Bearing outer face_	7.75"	7.45"
Magnet Weight lbs_	2.75	2.57
Estimated field adj. ratio_	none	2.5
Rating_	33/50 kW	same
Boost converter_	yes	No
High speed core loss_	high	low

In addition to the low loss performance improvement, this motor design eliminates the requirement for a boost converter, which not only simplifies the power electronics but enables a cost savings in the total drive system. The extra excitation coils and cores are made of copper wires and mild steel. Their total cost is compensated by the savings realized by a shorter stator core (1.875" as compared with the 3.3" of Prius) and shorter stator winding. The low-current (5 amps, maximum) control of the field excitation costs is minimal due to the low-current components required. This motor design enables a better performance motor with system cost savings.

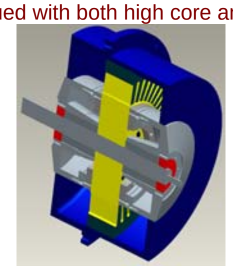
The design for the 16K RPM motor not only optimizes torque capability but also incorporates the ability to weaken the air gap flux density. The need for low core losses across a wide range of speed was also addressed in this design.

This design maximizes the thickness of the rotor punching bridges (material between the magnet slots in the rotor (see sketch below) to satisfy the mechanical stress requirements at the high speeds required of this machine. More leakage flux produced by the permanent magnets (PM) can go through these bridges so the air gap flux density produced by the PMs will be lower than other similar IPM machines like the lower-speed Prius motor.



This motor is still in the development stage. Validation data will be available after initial testing is completed this year. Please see our Annual report for additional information.

Our motor is intentionally designed for low air gap flux density at high speeds with no field excitation current applied This solves the high core loss problem of the existing Prius/Highlander-type, high-PM-flux-density, high-speed motors which are plagued with both high core and high d-axis current losses necessary for field weakening.



16,000 rpm Machine

Initial test results show: (1) The back emf can be controlled effectively through the external field excitation current with a range of current from zero to 5 amps, thus negating the necessity of using a boost converter to overcome high back emf. The air gap flux density can change up to 2.5 times at a given speed. This enables the motor to have all the advantages of both the existing strong PM reluctance (i.e., high power density, high back emf at high speed, high core loss) and the weak PM reluctance (i.e., low power density, low back emf, lower core loss) motors without their disadvantages. The additional circuitry necessary to supply the excitation current to the coils should cost less than ten dollars in production quantities. (2) The core and friction loss tests conducted show the benefits of lower air-gap flux density. For example, at 5000 rpm the core and friction loss is 200 W with zero field excitation as compared with 600 W at high field excitation for a high air gap flux density.

This inherently low air gap flux density motor design enables significantly lower core losses at high speeds. Yet at low speeds when high torque is needed the ability to enhance the field can dramatically boost the torque. The excitation coils coupled with this low air gap flux design enables the motor to be controlled or 'fine tuned' to operate in its highest efficiency areas across the torque/speed curve.

Additionally, if used in a vehicle architecture requiring a boost converter this motor can produce 250 kW output at 16,000 rpm. This significantly widens the possible applications for this type of motor.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 6***

Title: **Interior Permanent Magnet Reluctance Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: Seems relevant from what was presented.

Potential to Meet Technical Target: No

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: Looking for more information on assumptions and rationale for how the system will meet/beat goals.

Approach sufficiently innovative: No
If no, explain: Can't tell from information presented.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Quantify how total drive system will meet all the cost goals. Power electronics sound more complex, as is the rotor.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: The comparison of mass and size gives a foundation for a cost comparison with the Prius motor (see chart below).

	Prius	**ORNL**
Speed_	6000 rpm	16,000 rpm
Stator Lam. OD_	10.6”	same
Rotor OD_	6.375”	same
Core length_	3.3”	1.88”
Bearing to Bearing outer face_	7.75”	7.45”
Magnet Weight lbs_	2.75	2.57
Estimated field adj. ratio_	none	2.5
Rating_	33/50 kW	same
Boost converter_	yes	No
High speed core loss_	high	low

In addition to the low loss performance improvement, this motor design eliminates the requirement for a boost converter, which not only simplifies the power electronics but enables a cost savings in the total drive system. The extra excitation coils and cores are made of copper wires and mild steel. Their total cost is compensated by the savings realized by a shorter stator core (1.875” as compared with the 3.3” of Prius) and shorter stator winding. The low-current (5 amps, maximum) control of the field excitation costs is minimal due to the low-current components required. This motor design enables a better performance motor with system cost savings.

The prototype motor can be further reduced in mass and volume by redesigning the interface between the excitation coils and the motor housing. This improvement will reduce the cost to manufacture the motor by the elimination of some machining steps as well as raw materials.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

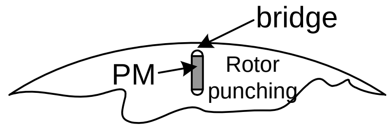
Additional Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 6***

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

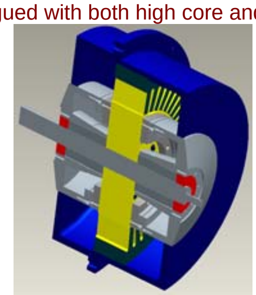
The design for the 16K RPM motor not only optimizes torque capability but also incorporates the ability to weaken the air gap flux density. The need for low core losses across a wide range of speed was also addressed in this design.

This design maximizes the thickness of the rotor punching bridges (material between the magnet slots in the Rotor (see below) to satisfy the mechanical stress requirements at the high speeds required of this machine. More leakage flux produced by the permanent magnets (PM) can go through these bridges so the air gap flux density produced by the PMs will be lower than other similar IPM machines like the lower-speed Prius motor.



This motor is still in the development stage. Validation data will be available after initial testing is completed this year. Please see our Annual report for additional information.

Our motor is intentionally designed for low air gap flux density at high speeds with no field excitation current applied This solves the high core loss problem of the existing Prius/Highlander-type, high-PM-flux-density, high-speed motors which are plagued with both high core and high d-axis current losses necessary for field weakening.



16,000 rpm Machine

Initial test results show: (1) The back emf can be controlled effectively through the external field excitation current with a range of current from zero to 5 amps, thus negating the necessity of using a boost converter to overcome high back emf. The air gap flux density can change up to 2.5 times at a given speed. This enables the motor to have all the advantages of both the existing strong PM reluctance (i.e., high power density, high back emf at high speed, high core loss) and the weak PM reluctance (i.e., low power density, low back emf, lower core loss) motors without their disadvantages. The additional circuitry necessary to supply the excitation current to the coils should cost less than ten dollars in production quantities. (2) The core and friction loss tests conducted show the benefits of lower air-gap flux density. For example, at 5000 rpm the core and friction loss is 200 W with zero field excitation as compared with 600 W at high field excitation for a high air gap flux density.

This inherently low air gap flux density motor design enables significantly lower core losses at high speeds. Yet at low speeds when high torque is needed the ability to enhance the field can dramatically boost the torque. The excitation coils coupled with this low air gap flux design enables the motor to be controlled or ‘fine tuned’ to operate in its highest efficiency areas across the torque/speed curve.

Based on the experience of building the prototype at ORNL it is anticipated that, the motor will not present any complicated manufacturing issues. This is certainly a concern with any design undertaken at ORNL. As design progresses and transitions to industry an industrial partner will be brought in to assist us in identifying and resolving these issues.

No issues with added gearbox complexity are expected. We do not foresee a more complex gearbox than the planetary gearbox that is currently used by some of the automotive manufacturers

Additionally, if used in a vehicle architecture requiring a boost converter this motor can produce 250 kW output at 16,000 rpm. This significantly widens the possible applications for this type of motor.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 6***

Title: **Interior Permanent Magnet Reluctance Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification:

Potential to Meet Technical Target: No

If no, explain: Not enough data provided. System to complex.

PI's Response to Relevance Questions/Comments: This motor is still in the development stage. Validation data will be available after initial testing is completed. Please see the Annual report for additional information.

Approach Rating (1-4): **2**

Approach Justification:

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses: Pushes complexity to gearbox.

Recommendations for Additions/Deletions to Project Scope:

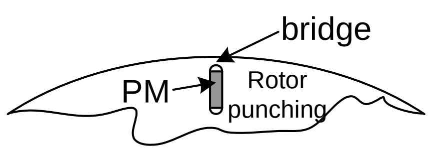
Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

No issues with added gearbox complexity are expected. We do not foresee a more complex gearbox than the planetary gearbox that is currently used by some of the automotive manufacturers.

The design for the 16K RPM motor not only optimizes torque capability but also incorporates the ability to weaken the air gap flux density. The need for low core losses across a wide range of speed was also addressed in this design.

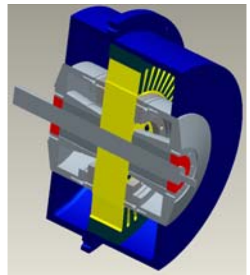
This design maximizes the thickness of the rotor punching bridges (material between the magnet slots in the rotor (see below) to satisfy the mechanical stress requirements at the high speeds required of this machine. More leakage flux produced by the permanent magnets (PM) can go through these bridges so the air gap flux density produced by the PMs will be lower than other similar IPM machines like the lower-speed Prius motor.



This motor is still in the development stage. Validation data will be available after initial testing is completed this year. Please see our Annual report for additional information.

Our motor is intentionally designed for low air gap flux density at high speeds with no field excitation current applied This solves the high core loss problem of the existing Prius/Highlander-type, high-PM-flux-density, high-speed motors which are plagued with both high core and high d-axis current losses necessary for field weakening.

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 6*



16,000 rpm Machine

Initial test results show: (1) The back emf can be controlled effectively through the external field excitation current with a range of current from zero to 5 amps, thus negating the necessity of using a boost converter to overcome high back emf. The air gap flux density can change up to 2.5 times at a given speed. This enables the motor to have all the advantages of both the existing strong PM reluctance (i.e., high power density, high back emf at high speed, high core loss) and the weak PM reluctance (i.e., low power density, low back emf, lower core loss) motors without their disadvantages. The additional circuitry necessary to supply the excitation current to the coils should cost less than ten dollars in production quantities. (2) The core and friction loss tests conducted show the benefits of lower air-gap flux density. For example, at 5000 rpm the core and friction loss is 200 W with zero field excitation as compared with 600 W at high field excitation for a high air gap flux density.

This inherently low air gap flux density motor design enables significantly lower core losses at high speeds. Yet at low speeds when high torque is needed the ability to enhance the field can dramatically boost the torque. The excitation coils coupled with this low air gap flux design enables the motor to be controlled or 'fine tuned' to operate in its highest efficiency areas across the torque/speed curve.

Based on the experience of building the prototype at ORNL it is anticipated that, the motor will not present any complicated manufacturing issues. This is certainly a concern with any design undertaken at ORNL. As design progresses and transitions to industry an industrial partner will be brought in to assist us in identifying and resolving these issues.

The prototype motor can be further reduced in mass and volume by redesigning the interface between the excitation coils and the motor housing. This improvement will reduce the cost to manufacture the motor by the elimination of some machining steps as well as raw materials.

The comparison of mass and size gives a foundation for a cost comparison with the Prius motor (see chart below).

	Prius	**ORNL**
Speed_	6000 rpm	16,000 rpm
Stator Lam. OD_	10.6"	same
Rotor OD_	6.375"	same
Core length_	3.3"	1.88"
Bearing to Bearing outer face_	7.75"	7.45"
Magnet Weight lbs_	2.75	2.57
Estimated field adj. ratio_	none	2.5
Rating_	33/50 kW	same
Boost converter_	yes	No
High speed core loss_	high	low

In addition to the low loss performance improvement, this motor design eliminates the requirement for a boost converter, which not only simplifies the power electronics but enables a cost savings in the total drive system. The extra excitation coils and cores are made of copper wires and mild steel. Their total cost is compensated by the savings realized by a shorter stator core (1.875" as compared with the 3.3" of Prius) and shorter stator winding. The low-current (5 amps, maximum) control of the field excitation costs is minimal due to the low-current components required. This motor design enables a better performance motor with system cost savings.

Additionally, if used in a vehicle architecture requiring a boost converter this motor can produce 250 kW output at 16,000 rpm. This significantly widens the possible applications for this type of motor.

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 10*

Title: **Interior Permanent Magnet Reluctance Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: "Field weakening with external magnet," "size and weight reduction with high speed," etc. are key to achieving DOE objectives.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: The approach of adding external magnetic field has been proposed in the past. Hong Kong U. has similar design. It would be good if this project shows some state-of-the-art technology comparison, not just Prius.

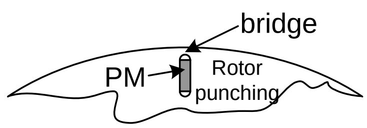
Approach sufficiently innovative: No

If no, explain: Several other research institutes have done similar design. The comparison needs to show the difference and distinct features.

PI's Response to Approach Questions/Comments: The ORNL patent attorney and the U.S. Patent office have examined our technology and granted several patents on the ORNL technology. The current technology, Lundel Motor, uses a brush type motor. We are unaware of the work going on at Hong Kong U, and will look into their technology.

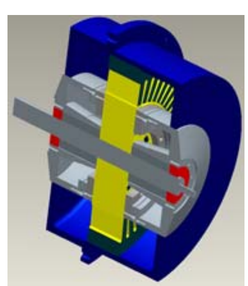
The design for the 16K RPM motor not only optimizes torque capability but also incorporates the ability to weaken the air gap flux density. The need for low core losses across a wide range of speed was also addressed in this design.

This design maximizes the thickness of the rotor punching bridges (material between the magnet slots in the rotor (see below) to satisfy the mechanical stress requirements at the high speeds required of this machine. More leakage flux produced by the permanent magnets (PM) can go through these bridges so the air gap flux density produced by the PMs will be lower than other similar IPM machines like the lower-speed Prius motor.



This motor is still in the development stage. Validation data will be available after initial testing is completed this year. Please see our Annual report for additional information.

Our motor is intentionally designed for low air gap flux density at high speeds with no field excitation current applied This solves the high core loss problem of the existing Prius/Highlander-type, high-PM-flux-density, high-speed motors which are plagued with both high core and high d-axis current losses necessary for field weakening.



16,000 rpm Machine

Initial test results show: (1) The back emf can be controlled effectively through the external field excitation current with a range of current from zero to 5 amps, thus negating the necessity of using a boost converter to overcome high back emf. The air gap flux density can change up to 2.5 times at a given speed. This enables the motor to have all the advantages of both the existing strong PM reluctance (i.e., high power density, high back emf at high speed, high core loss) and the weak PM reluctance (i.e., low power density, low back emf, lower core loss) motors without their disadvantages. The additional circuitry necessary to supply the excitation current to the coils should cost less than ten dollars in production quantities. (2) The core and friction loss tests conducted show the benefits of lower air-gap flux density. For example, at 5000 rpm the core and friction loss is 200 W with zero field excitation as compared with 600 W at high field excitation for a high air gap flux density.

This inherently low air gap flux density motor design enables significantly lower core losses at high speeds. Yet at low speeds when high torque is needed the ability to enhance the field can dramatically boost the torque. The excitation coils coupled with this low air gap flux design enables the motor to be controlled or 'fine tuned' to operate in its highest efficiency areas across the torque/speed curve.

Based on the experience of building the prototype at ORNL it is anticipated that, the motor will not present any complicated manufacturing issues. This is certainly a concern with any design undertaken at ORNL. As design progresses and transitions to industry an industrial partner will be brought in to assist us in identifying and resolving these issues.

No issues with added gearbox complexity are expected. We do not foresee a more complex gearbox than the planetary gearbox that is currently used by some of the automotive manufacturers.

The prototype motor can be further reduced in mass and volume by redesigning the interface between the excitation coils and the motor housing. This improvement will reduce the cost to manufacture the motor by the elimination of some machining steps as well as raw materials.

The comparison of mass and size gives a foundation for a cost comparison with the Prius motor (see chart below).

	Prius	ORNL
Speed_	6000 rpm	16,000 rpm
Stator Lam. OD_	10.6"	same
Rotor OD_	6.375"	same
Core length_	3.3"	1.88"
Bearing to Bearing outer face_	7.75"	7.45"
Magnet Weight lbs_	2.75	2.57
Estimated field adj. ratio_	none	2.5
Rating_	33/50 kW	same
Boost converter_	yes	No
High speed core loss_	high	low

In addition to the low loss performance improvement, this motor design eliminates the requirement for a boost converter, which not only simplifies the power electronics but enables a cost savings in the total drive system. The extra excitation coils and cores are made of copper wires and mild steel. Their total cost is compensated by the savings realized by a shorter stator core (1.875" as compared with the 3.3" of Prius) and shorter stator winding. The low-current (5 amps, maximum) control of the field excitation costs is minimal due to the low-current components required. This motor design enables a better performance motor with system cost savings.

Additionally, if used in a vehicle architecture requiring a boost converter this motor can produce 250 kW output at 16,000 rpm. This significantly widens the possible applications for this type of motor.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Simulation and analysis have been done to show superior performance. It's not clear if parasitic losses of auxiliary winding are included.

Accomplishments Sufficient: No

Significant Accomplishments During Year: I prefer simulation along with a sealed hardware model to verify the performance and claim.

PI's Response to Technical Accomplishments Questions/Comments: Excitation coil losses are calculated as I2R losses due to the DC excitation. The core for the winding will have losses due to local DC flux fluctuations.

Strengths: Initial design, analysis, and simulation have been accomplished.

Weaknesses: No experimental model to verify the claim. The hardware always has parasitic losses that are not included in the simulation model.

Reviewer Affiliation: **R&D** ***Reviewer's Ability to Rate (1-10):*** ***10***

Recommendations for Additions/Deletions to Project Scope: 1. Build hardware model. 2. Incorporate control algorithm and simulation with the auxiliary winding control. 3. Incorporate field analysis and power electronics and control into simulation for system level performance verification.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Initial tests indicate a wide field (air gap flux density) adjustment range, i.e., 2.5 times. Air gap flux density measurements were performed on the motor with no enhancement as well as being enhanced and weakened with the excitation coils. Additionally, back emf results were recorded at various RPM ranges again with no enhancement as well as being both enhanced and weakened. These results will be published in the Annual Report. Future testing will encompass the locked rotor torque testing, higher speed back emf results, motor losses under no load as well as the parasitic losses.

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 2***

Title: **Interior Permanent Magnet Reluctance Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification: Use of increased speed to reduce size, weight, and cost is very interesting, and both 6000 rpm and 16,000 rpm exceed Prius standard and meet or exceed short-term FreedomCAR goals.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Should choose one approach (16K rpm or 6K) for further work & put all resources there.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good back emf and output torque results for 16K rpm motor w/flexible field. Excellent study of mechanical stress on the motor. Interesting improvements in 6K rpm motor.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Good motor performance.

Weaknesses:

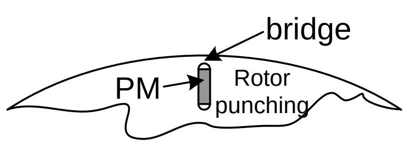
Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

The design for the 16K RPM motor not only optimizes torque capability but also incorporates the ability to weaken the air gap flux density. The need for low core losses across a wide range of speed was also addressed in this design.

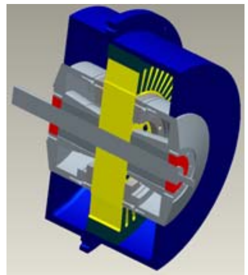
This design maximizes the thickness of the rotor punching bridges (material between the magnet slots in the rotor (see below) to satisfy the mechanical stress requirements at the high speeds required of this machine. More leakage flux produced by the permanent magnets (PM) can go through these bridges so the air gap flux density produced by the PMs will be lower than other similar IPM machines like the lower-speed Prius motor.



This motor is still in the development stage. Validation data will be available after initial testing is completed this year. Please see our Annual report for additional information.

Our motor is intentionally designed for low air gap flux density at high speeds with no field excitation current applied This solves the high core loss problem of the existing Prius/Highlander-type, high-PM-flux-density, high-speed motors which are plagued with both high core and high d-axis current losses necessary for field weakening.

Reviewer Affiliation: **R&D** *Reviewer's Ability to Rate (1-10):* **2**



16,000 rpm Machine

Initial test results show:
(1) The back emf can be controlled effectively through the external field excitation current with a range of current from zero to 5 amps. Thus negating the necessity of using a boost converter to overcome high back emf. The air gap flux density can change up to 2.5 times at a given speed. This enables the motor to have all the advantages of both the existing strong PM reluctance (i.e., high power density, high back emf at high speed, high core loss) and the weak PM reluctance (i.e., low power density, low back emf, lower core loss) motors without their disadvantages. The additional circuitry necessary to supply the excitation current to the coils should cost less than ten dollars in production quantities. (2) The core and friction loss tests conducted show the benefits of lower air-gap flux density. For example, at 5000 rpm the core and friction loss is 200 W with zero field excitation as compared with 600 W at high field excitation for a high air gap flux density.

This inherently low air gap flux density motor design enables significantly lower core losses at high speeds. Yet at low speeds when high torque is needed the ability to enhance the field can dramatically boost the torque. The excitation coils coupled with this low air gap flux design enables the motor to be controlled or 'fine tuned' to operate in its highest efficiency areas across the torque/speed curve.
Based on the experience of building the prototype at ORNL it is anticipated that, the motor will not present any complicated manufacturing issues. This is certainly a concern with any design undertaken at ORNL. As design progresses and transitions to industry an industrial partner will be brought in to assist us in identifying and resolving these issues.
No issues with added gearbox complexity are expected. We do not foresee a more complex gearbox than the planetary gearbox that is currently used by some of the automotive manufacturers

The prototype motor can be further reduced in mass and volume by redesigning the interface between the excitation coils and the motor housing. This improvement will reduce the cost to manufacture the motor by the elimination of some machining steps as well as raw materials.

The comparison of mass and size gives a foundation for a cost comparison with the Prius motor (see chart below).

	Prius	ORNL
Speed_	6000 rpm	16,000 rpm
Stator Lam. OD_	10.6"	same
Rotor OD_	6.375"	same
Core length_	3.3"	1.88"
Bearing to Bearing outer face_	7.75"	7.45"
Magnet Weight lbs_	2.75	2.57
Estimated field adj. ratio_	none	2.5
Rating_	33/50 kW	same
Boost converter_	yes	No
High speed core loss_	high	low

In addition to the low loss performance improvement, this motor design eliminates the requirement for a boost converter, which not only simplifies the power electronics but enables a cost savings in the total drive system. The extra excitation coils and cores are made of copper wires and mild steel. Their total cost is compensated by the savings realized by a shorter stator core (1.875" as compared with the 3.3" of Prius) and shorter stator winding. The low-current (5 amps, maximum) control of the field excitation costs is minimal due to the low-current components required. This motor design enables a better performance motor with system cost savings.

Additionally, if used in a vehicle architecture requiring a boost converter this motor can produce 250 kW output at 16,000 rpm. This significantly widens the possible applications for this type of motor.

Reviewer Affiliation: Industry

Reviewer's Ability to Rate (1-10): 9

Title: **Low Thermal Resistance IGBT Structure**

Presenter: **Keith Gawlik**

Laboratory/Company: **NREL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Capability to realize >100W/cm2 using direct DBC cooling via jet impingement is an excellent near term (~3-5yr) project. I started the review a bit circumspect over the use of jet spray and jet impingement techniques. However, the use of 10m/s spray is readily achievable and robust in the automotive environment. I would think even the humble windshield washer pump can deliver that. At this point I am confident the process is viable for automotive.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Joint collaboration with Semikron gives this work more practical relevance and is an excellent working arrangement. So the approach taken is appropriate. Personally, the concept of putting the die into a shower is appealing and makes very good engineering sense. Attack the heat problem at its very core - the semiconductor die.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Need to get these experimental validation steps into work and get with it. I can see that working with John Mookken at Semikron as a real leveraging opportunity and I encourage that. Looking forward to hearing of many successes in this endeavor.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Most important to me was knowing the machined nozzle plate works.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: National laboratory and industrial partner collaboration.

Weaknesses: Perhaps a little timid in getting this going. I'd say full steam - or should that be full spray stream - ahead. Don't hold back!

Recommendations for Additions/Deletions to Project Scope: Encourage it to completion. The competition is not going to wait.

Additional Comments: Check out the headlines: "Monday, September 11, 2006/ Richard Williamson (Scripps Howard News Service). Five months after sales began, the 2007 Toyota Camry Hybrid has found 12,409 buyers. Reading on to the last sentence: Bottom Line: Hybrid power is now mainstream." My take on this - Toyota has hybridized a mass market vehicle successfully. Hybrids are indeed mainstream now.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 8*

Title: **Low Thermal Resistance IGBT Structure**

Presenter: **Keith Gawlik** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Good near-term benefit project to use 105°C coolant. Gives "reality-check". Feedback useful for longer-term developments.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Good plan overall, but I would have added evaluation of anti-wear coatings on copper, in parallel with other activities.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Used results from jet testing on small scale to develop a detailed design for complete inverter cooling. Nothing was done to minimize erosion, however. Could this have been done on the jet impingement test, with various coatings?

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Designed nozzle plate for uniform jet velocities, and built prototype module.

PI's Response to Technical Accomplishments Questions/Comments: We will develop a plan to evaluate the impact of jets on erosion and investigate alternatives as necessary.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Look at effect of vibration on sealing, connections, etc. Evaluate system in transient power cycling.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Experimental validation and evaluations that address issues such as actual performance, reliability, and erosion will be key areas of focus for this project in FY07. System integration issues will also be evaluated and reported on.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 2***

Title: **Low Thermal Resistance IGBT Structure**

Presenter: **Keith Gawlik** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **2**

Relevance Justification: The project has the potential of delivering a technical breakthrough. There are many possible negative consequences that make adoption in industry questionable.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: Experimental validation and evaluations that address issues such as actual performance, reliability, and erosion will be key areas of focus for this project in FY07. System integration issues will also be evaluated and reported on.

Approach Rating (1-4): **4**

Approach Justification: Technical approach appears to be well formulated to deal with the many challenges through combination of analytical design and empirical efforts.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Excellent progress on analytical design. Good progress on fabricating prototype. Fair progress on empirical validation. Hope to get the nozzle plate by "tomorrow."

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Thermal and mechanical design complete. Fab of prototype contracted.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **Low Thermal Resistance IGBT Structure**

Presenter: **Keith Gawlik** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Jet cooling appears to have sufficient opportunity to gain power density.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Teaming with industry in doing both modeling and experimentation is reasonable.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: As the work so far is just simulation, there is still the issues of how well the proposed system performs in practice.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Experimental validation and evaluations that address issues such as actual performance, reliability, and erosion will be key areas of focus for this project in FY07. System integration issues will also be evaluated and reported on.

Strengths:

Weaknesses: Lack of hardware implemented is a weakness.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **Low Thermal Resistance IGBT Structure**

Presenter: **Keith Gawlik** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: Long-term testing of structure will be required to verify there are no leaks. How big and costly is the pump for this system? Does this pump get included in system cost & size goals for FreedomCAR goals?

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: Experimental validation and evaluations that address issues such as actual performance, reliability, and erosion will be key areas of focus for this project in FY07. System integration issues will also be evaluated and reported on.

Approach Rating (1-4): **3**

Approach Justification: Is long-term sealing issues being addressed? Also, degradation of fluid, contamination, and pressure drop. What would be an acceptable pressure drop for an OEM? DOE pressure drop goal 0.73 PSI.

Approach sufficiently innovative: Yes/No
If no, explain: Will it meet DOE pressure drop goal? See Ballard Slide #6.

PI's Response to Approach Questions/Comments: Our preliminary investigations into sealing appear promising, however additional experimental validation and evaluations that address issues such as actual performance, reliability, and erosion will be key areas of focus for this project in FY07. System integration issues will also be evaluated and reported on.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: The approach is well thought out but needs measured data.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Low Thermal Resistance IGBT Structure**

Presenter: **Keith Gawlik** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **1**

Relevance Justification: While thermal management is important for the FreedomCAR program to meet its goals, it does not appear that this research project will substantially contribute to the knowledge base or assist in meeting the goals. Vision of the FreedomCAR program is to conduct research that is stretch, long range, high risk, and can use technologies and capabilities that national labs uniquely possess. This project seems more like an evolutionary project that component suppliers ought to be conducting.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: The work is carefully thought out and appears to be well executed leading to possible solution to thermal management problems.

Approach sufficiently innovative: No

If no, explain: See Relevance Justification above.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: PI is doing good analytical work and will need to wait for hardware to see if promise is proved out in testing.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses: Ought to be outside the scope of federally funded research.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM **Reviewer's Ability to Rate (1-10): 5**

Title: **Low Thermal Resistance IGBT Structure**

Presenter: **Keith Gawlik** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 3

Relevance Rating (1-4): **1**

Relevance Justification: Not a long-range and high-risk R&D.

Potential to Meet Technical Target: No

If no, explain:

PI's Response to Relevance Questions/Comments: We have a portfolio of technologies that we are developing – some are more long term / high risk than others. The high risk technologies tend to be criticized for not considering the practical aspects of integration into an automotive application. This project provides a platform to evaluate jet cooling technology integrated into an automotive apparatus. Understanding of these implementation issue will provide valuable feedback to the developers of more “risky” technologies – such as reliability, sealing, erosion, etc.

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **1**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 7***

Title: **Low Thermal Resistance IGBT Structure**

Presenter: **Keith Gawlik** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: I would like to see comprehensive assessment of system implications including cost. Great effort to demonstrate, though this is not a stretch project so real value is in getting the info above.

Accomplishments Sufficient:

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Experimental validation and evaluations that address issues such as actual performance, reliability, and erosion will be key areas of focus for this project in FY07. System integration issues will also be evaluated and reported on.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM **Reviewer's Ability to Rate (1-10): 8**

Title: **Low Thermal Resistance IGBT Structure**

Presenter: **Keith Gawlik** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 4

Relevance Rating (1-4): **1**

Relevance Justification:

Potential to Meet Technical Target: No

If no, explain: Not far reaching.

PI's Response to Relevance Questions/Comments: We have a portfolio of technologies that we are developing – some are more long term / high risk than others. The high risk technologies tend to be criticized for not considering the practical aspects of integration into an automotive application. This project provides a platform to evaluate jet cooling technology integrated into an automotive apparatus. Understanding of these implementation issue will provide valuable feedback to the developers of more "risky" technologies – such as reliability, sealing, erosion, etc.

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **1**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year: This seems to have been covered before.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D **Reviewer's Ability to Rate (1-10): 10**

Title: **Low Thermal Resistance IGBT Structure**

Presenter: **Keith Gawlik** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Direct liquid jet cooling to the bottom of the DBC is necessary for T < 125°C operation in 90°C-105°C coolant as there is no way to achieve this with passive thermal contact from the die to heat sink w/any known thermal interface material.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Direct liquid jet cooling promises very high cooling capability but need to address reliability when impinging high pressure liquid on the bottom of DBC. Issues include stress on die, stress on interconnect, and erosion of DBC surface.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: Experimental validation and evaluations that address issues such as actual performance, reliability, and erosion will be key areas of focus for this project in FY07.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Functional prototype is ready for test that has been refined through simulation & experiment the results of which were shown. Still need extensive reliability work to assess stress on die (for dye cracking), stress on interconnect (for spring failure), and erosion of DBC surface.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Prototype design.

PI's Response to Technical Accomplishments Questions/Comments: Experimental validation and evaluations that address issues such as actual performance, reliability, and erosion will be key areas of focus for this project in FY07.

Strengths: Thermal modeling showing excellent heat flux cooling moving toward prototype.

Weaknesses: No modeling/experiment addressing interconnect reliability, die cracking, and DBC erosion as a result of direct liquid impingement.

Recommendations for Additions/Deletions to Project Scope: Significant reliability work must be added to address mechanical failure mechanisms discussed above.

Additional Comments: Insufficient slides. The presenter discussed an extensive structural analysis but provided no data, or summaries, just a few talking points..

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Weakness: - see above.

Additional Comments: We will provide additional detail and publish this information.

Reviewer Affiliation: R&D **Reviewer's Ability to Rate (1-10): 10**

Title: **Low Thermal Resistance IGBT Structure**

Presenter: **Keith Gawlik** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: This work is fundamental to achieving the power density goals of the FreedomCAR program.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: I believe the logical, careful approach used here is very sound. My primary concern is the limitation to jets.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: The amount of work completed seems quite good. The simulation work is reasonable and appears well done. The fluidic design appears solid.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Prototype design. Tight collaboration with industry partner.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments: looking forward to the report. Really looking forward to data!!

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Experimental validation and evaluations that address issues such as actual performance, reliability, and erosion will be key areas of focus for this project in FY07.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: There are many more issues using single phase (oscillating) jets and jet spray vs. air cooling for future HEV, PITEV, and FCHV applications. Cost and complexity are high on the list. Capable of high heat flux removal.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: Certainly, with jets/sprays issues such as system complexity, cost, and reliability will all have to be addressed. We plan on a system level modeling to assess these various issues in FY07.

Approach Rating (1-4): **3**

Approach Justification: For direct air cooling a previous project (DB's) showed that it takes 93 W power to remove 200 W heat (COPN~2). For both osc. Jet and jet spray we need this same metric.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: This is an important point. These were not presented at the annual review, but we have measured the pressure drop and the parasitic power consumption due to the jets. We will cast the performance of the different fluidic nozzles in the form of a coefficient of performance metric.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Need more content on what amount of effort it will take to integrate these approaches into an integrated power electronic inverter.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Again, this is an important point. We have a project in FY07 which looks at the system level modeling and system level implications of using these various cooling approaches.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Identify time line when the various jet spray methods can be downselected to most favorable approach. Must include COP.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: The point regarding COP is certainly noted. We will come up with a metric to characterize the performance of different nozzles.
Regarding the timeline, the numerical and experimental data from the different cooling approaches will be fed into an overall systems level modeling approach. This will help determine the most favorable approach from the viewpoint of performance, system complexity and cost.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 1***

Title: **Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification: Goals are relevant. Technology might be relevant, but questionable for adoption in auto industry.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: We plan to assess the issue of feasibility of adoption in the auto industry via a project which focuses on the system level implications of these cooling approaches.

Approach Rating (1-4): **3**

Approach Justification: Approach basically modeling with industrial collaboration to remain relevant.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Results are useful contribution, especially for system engineering. Less useful for component engineering.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Working CFD simulation with quantitative results.

PI's Response to Technical Accomplishments Questions/Comments: It is not very clear what the reviewer has in mind when he/she mentions component engineering.

We believe we have also made significant progress in single phase self-oscillating jet experiments as well as in the fabrication of experimental apparatus which will enable two-phase jet/spray

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 8***

Title: **Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Spray and two phase cooling (either refrigerant or WEG) hold promise of superior heat removal.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: Certainly, two-phase jets/sprays look promising from a heat transfer viewpoint.

Approach Rating (1-4): **3**

Approach Justification: Modeling gives an idea of which techniques hold sufficient hope for success.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: This is true. For example, we performed numerical simulations with R134a jet in the nucleate boiling regime, and it revealed conditions under which we can dissipate 200 W/cm2 while keeping the die temperature close to 125°C.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: The self-oscillating jets sound good, but at reasonable distances for these voltages, it looks as if the benefits are non-existent.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: It is not clear which voltages the reviewer is talking about. Certainly, we need to fully and systematically characterize the performance of the self-oscillating jets over a range of velocities and target distances. We intend to do this in FY07.

Strengths: Innovative

Weaknesses: Need to recognize how the system is impacted, including appropriate spacing for ~500 V systems.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: We plan to explore the system level implications of the cooling schemes we are investigating. As mentioned previously, we are planning a system level modeling to investigate the impact on these cooling approaches at the system level.

Reviewer Affiliation: Industry **Reviewer's Ability to Rate (1-10): 7**

Title: **Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: Modeling is good, data is better.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: Having experimental data is certainly desirable. This is the reason we started experiments in FY06 and plan to continue these experiments in both the single phase and two-phase regime.

Approach Rating (1-4): **3**

Approach Justification: At 200-250 watt/cm2 power dissipation can the power devices generate this much heat flux? What limits nozzle diameter size? How is the quality of cooling fluid maintained? Can you spray parts for 7500 hours to verify degradation?

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

(a) The FreedomCAR goal states a heat flux goal of 200 to 250 W/cm2 from the silicon die. The presumably is for future generation of power electronic devices.
(b) The nozzle diameter cannot be very small because these could potentially lead to problems related to clogging. For jet impingement, the velocity is a very critical parameter in determining the heat transfer from the target surface. If the nozzle diameter is very large, then for a given flow rate, the jet velocity will be small and this will lead to low heat transfer rates from the target surface. The size of the target also plays an important role in determining the jet nozzle diameter. Extensive work has been published in the literature examining the impact of nozzle diameter on the target surface heat transfer.
(c) In our lab, we have filters installed to maintain the quality of the cooling fluid.
(d) This is an important question and relates to long term reliability of liquid impingement cooling. We are contemplating performing experiments to test the impact of jet/spray impingement on the target surface degradation. It is not fully clear at this point whether we will be able to continuously impinge jets on a target surface for 7500 hours. This requires some further thinking.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Needs measured data.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: We have some experimental data with single phase jets. We will have more single phase and two-phase data in FY07.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **3**

Relevance Justification: While thermal management is important for the FreedomCAR program to meet its goals, it does not appear that this research project will substantially contribute to the knowledge base or assist in meeting the goals. The title of the research is promising but there was no report of significant progress on modeling of a two phase spray.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: The reviewer's comments seem to have been cut off. It is not clear why the reviewer feels that the project will not contribute to the knowledge base.

Approach Rating (1-4): **2**

Approach Justification: Approach seems sound but much more detail is needed in the modeling to better explain and predict cooling. Would like to see modeling expanded with more details in two phase cooling.

Approach sufficiently innovative: No
If no, explain: Not detailed enough

PI's Response to Approach Questions/Comments: As mentioned previously, we have done extensive CFD modeling of two-phase jet impingement cooling. We would be happy to provide technical reports as well as papers that have come out of the work. It is not clear what details the reviewer is looking for. Due to the time constraints, it is not possible to elaborate on the results during the annual review meeting presentation.

We would be happy to provide further details through an appropriate avenue.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Models on jet impingement are not new.

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Actually, CFD modeling of jet impingement involving nucleate boiling is quite novel. To the best of our knowledge, we have not seen a single publication in the open literature dealing with jet impingement cooling of the IGBT package in the nucleate boiling regime.

Strengths:

Weaknesses: Need to refocus on two phase cooling. A complete understanding of this would be beneficial.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: In collaboration with Fluent Inc., we have spent a great deal of time in FY05 and FY06 modeling jet impingement involving nucleate boiling. In FY07, we plan on conducting experiments with jets/sprays in the nucleate boiling regime.

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): Reviewer did not provide number.

Relevance Rating (1-4): **3**

Relevance Justification: Modeling could be valuable to OEMs, specifically 2-phase cooling.

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments:

We have done extensive modeling of impinging jets involving nucleate boiling. This has also been applied to study IGBT package cooling using R134a and the code can easily be used to study other fluids such as HFE7100/7200 and maybe even glycol-water.

We have demonstrated conditions under which R134a could be used to dissipate up to 200 W/cm2 heat flux from the silicon die while maintaining the die temperature close to 125°C.

This is a significant contribution, since in the open literature there is very little CFD modeling of impinging jets in the nucleate boiling regime.

It is not clear why the reviewer feels jets/sprays do not have the potential to meet the target.

Approach Rating (1-4): **2**

Approach Justification: Not enough data to evaluate.

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments:

We are adopting parallel approaches to meet the program goals. This includes modeling as well as experiments. We have done extensive modeling of jets in the single phase as well as boiling regime. These results are documented in a conference paper and a draft is also in the process of being submitted to a journal.

On the experimental front, we are performing experiments with single phase self-oscillating jets in an attempt to enhance heat transfer coefficients over steady jets. An apparatus has also been fabricated to enable two-phase jet and spray experiments with fluids such as R134a, HFE7100/7200.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Insufficient data on 2-phase cooling.

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Extensive CFD simulations have been performed of impinging jets involving nucleate boiling. This includes experimental validations of the CFD code, and application to IGBT package cooling via coolants such as R134a. We will perform experiments with two-phase jets/sprays in FY07. The apparatus for these two-phase experiments has been fabricated.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 7***

Title: **Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: Two-phase has potential. Single phase is old news.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: Single phase steady jet impingement has been studied extensively in the literature, but the goal here is to explore technologies which have the potential to meet FreedomCAR goals and also are attractive from the viewpoint of system cost, complexity and overall performance.

Also, single phase self-oscillating jets has not been explored much in the literature and it has the potential to be beneficial.

Significant effort is also being put into two-phase jets/sprays.

Approach Rating (1-4): **2**

Approach Justification: Literature search is good but seems to have taken too long.

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments: It is not clear which literature search the reviewer is referring to.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Need to see more data on 2-phase.

Accomplishments Sufficient:

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: We have performed detailed CFD modeling of two-phase jets and we will be performing experiments with 2-phase jets/sprays in FY07.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 8*

Title: **Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10):

Relevance Rating (1-4): **2**

Relevance Justification:

Potential to Meet Technical Target: No

If no, explain: This could be a great project. Need more detail work on 2-phase cooling because no one really has this type of cooling. Jet impingement I have seen many times before.

PI's Response to Relevance Questions/Comments: We have performed detailed CFD modeling of jet impingement cooling in the nucleate boiling regime. In FY07, we plan to perform experiments with two-phase jets/sprays using the apparatus that has been fabricated in FY06.

The important issue is meeting FreedomCAR goals. While single phase steady jets have been studied extensively in the literature, concepts such as self-oscillating jets are relatively untouched.

Approach Rating (1-4): **2**

Approach Justification:

Approach sufficiently innovative: No
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **1**

Technical Accomplishment and Progress Justification: none

Accomplishments Sufficient: No
Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 9***

Title: **Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Spray cooling is one of the more promising techniques for providing significant cooling of power electronics. Has good chance of meeting FreedomCAR goals. Slide 19 shows how h=55000 provides T of 130°C for a T fluid of 105°C thereby coming very close to meeting FreedomCAR goals of using a 125°C module at a coolant temp of 105°C.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: Jet/spray cooling does hold a lot of promise to meet the FreedomCAR goals.

Approach Rating (1-4): **3**

Approach Justification: Focus on both single & double phase jets, along with self oscillating jets is good. Oscillating jet cooling is promising. Still not sure about the reliability of the interconnect holding the die to the substrate when the jet is impinging on the back of the die at high pressure. May lead to die cracking or interconnect fatigue.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments: Reliability is certainly an issue which will have to be addressed.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Substantial modeling has been done on the heat flow vs ΔT. Examination of heat transfer coefficient vs. distance and nozzle type is excellent. Excellent demonstration of the value of single phase, self-oscillating jets & developing a partnership with a company to provide them.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Demonstration of value of self-oscillating single jets and the development of a relationship w/a manufacturer.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Demonstrates single-phase, self-oscillating glycol-water spray cooling shows promise for cooling rates needed for FreedomCAR.

Weaknesses: Reliability issues on packaging due to being subjected to jet impingement has not been sufficiently addressed.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 10*

Title: **Modeling Two-Phase Spray and Jet Impingement Cooling/Modeling**

Presenter: **Sreekant Narumanchi** ***Laboratory/Company:*** **NREL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification: Technology like this is required to reach FreedomCAR goals.

Potential to Meet Technical Target: Yes-maybe

If no, explain: You are ignoring key packaging issues.

PI's Response to Relevance Questions/Comments: Actually, the project has different levels. We have done extensive modeling of both single phase and boiling jets and applied the modeling to a realistic IGBT package. For self-oscillating jet experiments, we feel it is better to first demonstrate the concept on a test surface and if significant benefits are obtained, then move to the IGBT package cooling in an inverter.

We have a different project where a steady jet impingement is being explored for cooling the IGBT package. In conjunction with Semikron, the cooling scheme is being incorporated into a Semikron inverter. This accounts for all the packaging issues that the reviewer is referring to. We do feel that new concepts should first be demonstrated on a test surface and then moved to the actual package/assembly.

Approach Rating (1-4): **3**

Approach Justification: Over all, this work is important and the simulations are useful. It is not clear that your simulations are really extensible to other flows/geometries experiments. Not realistic!! Probably 30-100% reduction in performance.

Approach sufficiently innovative: Yes/No

If no, explain: But - there's a lot of data in the literature about jet impingement-why reinvent the wheel?? It seems that you cold have started further along by doing a more careful literature search.

PI's Response to Approach Questions/Comments: The CFD simulations of single phase jets as well as boiling jets can be extended to any type of geometries. Regarding the single phase jet experiments (self-oscillating jets), a simple target surface is chosen to conduct the experiments due to the reasons mentioned above. We do not believe it is wise to go straight to inverter cooling without thoroughly establishing some merit on a simple set up.

The reviewer's point about 30 to100% reduction in performance in an actual geometry is relevant.

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: The simulations are good, innovative and useful. Excellent experimental facilities established for academic testing.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Simulations are important contribution. Work with self-oscillating jets is significant.

PI's Response to Technical Accomplishments Questions/Comments: We do not believe that we are reinventing the wheel. There is not much in the literature regarding the heat transfer performance of self-oscillating jets.
Our CFD modeling efforts in nucleate boiling in impinging jets is quite novel - there is very little in the open heat transfer literature in regards to CFD modeling of impinging jets in the nucleate boiling regime. We believe this is an important contribution to power electronics cooling as well as the general heat transfer literature.

Strengths:

Weaknesses: Too academic.

Recommendations for Additions/Deletions to Project Scope: Verify simulations for other geometries. Practical packaging.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Again, we believe the project has two stages – one for demonstration on a simpler test setup, and another for demonstration in an actual inverter. As an example, if oscillating jets are conclusively better than steady jets on the simpler test setup, then we will test its performance in an inverter.

We have presented numerical simulations for the IGBT package – it is not clear what other geometries the reviewer is referring to. This certainly could happen.

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 10*

Title: **Polymer Film and Nano-Dielectric Capacitors**

Presenter: **Bruce Tuttle** *Laboratory/Company:* **SNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: Good, but the development timeline runs too far into future. Onshore OEMs will need good capacitor technology before 2009. After 2009, HEV & PHEV will be good fraction of market. Need more sooner.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Well developed and sound program plan. Applications don't have the luxury of long development schedule times.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Incremental improvements, need revolutionary impressive material selection matrix and technology comparisons.

Accomplishments Sufficient: No

Significant Accomplishments During Year: How can this be accelerated to completion sooner?

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: It has been very good to see Toyota move away from aluminum electrolytics to film-type capacitors. Pressing need exists to get a knee-up on Toyota to improve our competitiveness.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 3***

Title: **Polymer Film and Nano-Dielectric Capacitors**

Presenter: **Bruce Tuttle** ***Laboratory/Company:*** **SNL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **3**

Relevance Justification: Good S&T effort with perhaps somewhat better industrial outlook. This project might have greater impact on power supplies than automotive.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Technical approach appears adequate for objectives. Only concern is the splitting of resources between two technologies. Typical S&T or risk reduction as claimed?

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Project seems to have a sense of urgency; even if the approach may cause some de-focus.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Multilayer prototypes under test. High temperature properties promising.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Polymer Film and Nano-Dielectric Capacitors**

Presenter: **Bruce Tuttle** ***Laboratory/Company:*** **SNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Research to find high temperature tolerant, low cost, easily manufactured capacitors is critical to meeting the goals of the FreedomCAR program and to the ability of OEMs to offer affordable, fully functional HEVs to customers.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Good approach. Noteworthy that PI recognized need to make go/no go decision on certain materials/approaches and is willing to terminate work that is not likely to meet the FreedomCAR goals.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Need further research work to assess temperature capability of nanoceramic materials.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Willingness to make go/no go decisions.

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Although we have shown that the nanoceramic materials have low loss and can withstand FreedomCAR operating voltages at high temperatures, we agree with the reviewer that further research work is needed to address the temperature capabilities of these materials. In FY07 we are again partnering with Honeywell to manufacture more multilayer nanoceramic capacitors that will be tested under the full range of FreedomCAR operating temperatures.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Polymer Film and Nano-Dielectric Capacitors**

Presenter: **Bruce Tuttle** ***Laboratory/Company:*** **SNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: Data presented is insufficient to judge the merit of this project.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: none

Approach sufficiently innovative: No
If no, explain: No data is available to support.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: During FY06 two different nanoceramic dielectrics were developed that exhibited excellent dielectric properties at high temperature (150ºC) and could withstand the 600 volts required for DC bus capacitor operation. Prototype multilayer capacitors were fabricated in collaboration with Honeywell with a similar number of layers that will be required for FreedomCAR DC bus capacitors. Three different polymer film chemistries were developed this past year. Two of these chemistries exhibited excellent loss at high temperatures (150ºC). In FY07, we will investigate additions to these polymers that will enhance flexibility such that wound capacitors can be evaluated in inverter environments. We have a decision point scheduled at the end of FY07 to either continue or discontinue our polymer film efforts.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 8***

Title: **Polymer Film and Nano-Dielectric Capacitors**

Presenter: **Bruce Tuttle** ***Laboratory/Company:*** **SNL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **3**

Relevance Justification: Need more detailed data.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification:

Approach sufficiently innovative: Yes
If no, explain: Assumes data exists.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: We have outlined a reasonable project plan for the fabrication of prototype capacitors in FY07. Once the prototype capacitors are proven to meet FreedomCAR requirements, we have already made contact with larger volume suppliers. These suppliers include Hydrosize, Inc. for polymer film solutions, Brady Corporation for polymer film capacitor fabrication and Honeywell for nanoceramic capacitor fabrication. Because of our advance planning with industry we should make rapid progress towards FreedomCAR goals.

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 9***

Title: **Polymer Film and Nano-Dielectric Capacitors**

Presenter: **Bruce Tuttle** ***Laboratory/Company:*** **SNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Low cost, high reliability, high power density, thermally stable capacitors remain a critical limitation to coolant-free power module development.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Addressing both film and ceramic approaches is good and the types and varieties of materials examined was very good. Now there is a need to focus on just the one or two most promising approaches and move forward on manufacturing prototype caps for analysis.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Appears that all the original polymer films proposed have been evaluated and found not to have sufficient temp stability or formability. If norborene does not meet the needs of FreedomCAR, the polymer track should be terminated to free up resources for the more promising PLZT approach. Focus on PLZT should be on achieving cost and benign failure mechanism targets with this potential high cost approach.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Developing norborene polymer chemistry; assessing PLZT caps.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Good development work in partnering with Honeywell and DuPont for improved PLZT caps.

Weaknesses: Need characterization data on prototype norborene caps to determine if they actually meet the promise and to make programmatic decision.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D **Reviewer's Ability to Rate (1-10): 9**

Title: **Polymer Film and Nano-Dielectric Capacitors**

Presenter: **Bruce Tuttle** ***Laboratory/Company:*** **SNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Good potential on nano-ceramic dielectric for its high density over state-of-the-art film and ceramic capacitors.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Developed nanopowder for multi-layer ceramic capacitor with high dielectric constant; developed high temp polymer films.

Approach sufficiently innovative: No

If no, explain: Scaling can be a major issue with only 0.2 µF achieved today. 2000 µF would be impossible to achieve in foreseeable future.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Evaluation on different materials have been done under different temperatures and frequencies. Built 0.2 µF PLZT capacitor to prove the concept Study on nanoceramic dielectric is underway.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Need a larger size prototype to prove the concept.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Understanding of material property; process of nano-material.

Weaknesses: Scaling up the capacitor size.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Thermal Control for Inverters and Motors**

Presenter: **John Hsu/Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Breaks in-box thinking on inverter form factor with can-like structure, ring type capacitor and floating loop cooling.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Good application of custom electronics capacitor. When do we see this project include the advanced capacitor developments? The combination will be a major advancement in packaging and thermal performance.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: Currently the advanced capacitor developments are addressing high temperature issues. This direct cooling and new packaging approach is specifically designed to reduce the environmental temperature to allow present capacitor technologies to be viable. As the advanced capacitors become available in usable inverter sizes, they can be tested as part of this cooling/packaging effort. The smaller value capacitors can be tested now in direct contact cooling for ripple current and material compatibility as they are made available to us.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: The can-style package is interesting, but do we know what form factor inverter package makes best use of the floating loop cooling method? I'd like to see the project address INV form factors from silos to donut-type to notebook-style flat pack. Is there a benefit?

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: The cylindrical housing shape matches the hollow-cylinder capacitor shape well, promoting a good power electronics packaging concept. It is also a good shape for medium and high pressure coolant housing requirements. A "donut" shape would also be a decent fit for this concept. The flat pack presents problems when trying to house medium and high pressure coolants due to structural requirements for the vessel.

We also considered the tilt angle requirement of the vehicle to ensure the availability of refrigerant at any practical tilt angle of the vehicle.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: How high a voltage would the internal components be capable of without degrading the working (R134a) fluid properties? Conversely, does the presence of R134a facilitate operating at higher inverter voltage, say 1.2 kV dc?

Additional Comments: It is not clear today where Toyota will go with their single mode power split inverter system voltage, but the trend is clearly higher. Trend has been 274 Vdc to 400 Vdc to 650 Vdc today. Electronics cost and thermal burdens will be lower at higher voltages. Combining the benefits of floating loop with elevated voltage may facilitate a technology leap.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Please see ORNL report "ORNL-TM-2005-219", a study previously performed on various refrigerants/coolants and their dielectric capabilities. The dielectric strength of R134a is high (approx 7 kV/mil), for both the liquid and vapor state. This should pose no problem for operating at 1.2 kV DC.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10):*** ***Reviewer did not provide a number.***

Title: **Thermal Control for Inverters and Motors**

Presenter: **John Hsu/Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Two-phase cooling has great potential for increasing power density. The floating loop concept takes advantage of existing hardware on the vehicle, which gives it a cost and implementation advantage.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Good plan layout, using parallel efforts where possible.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Very creative approach, and significant improvement of power density.

Accomplishments Sufficient:

Significant Accomplishments During Year: Demonstrated 2x power density improvement.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Suggest you benchmark the continental ISAD 2-phase cooled inverter, in production on GM full-size pick-ups ("contractor special" option) Also, suggest you address the sealing issues that are potential barriers to using higher pressures. (current ISAD Inverter has had problems in this area).

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: ORNL recognizes that feed-thru terminals for high pressure/high current are an issue and are currently addressing this problem and working on a solution. The ORNL laboratory models that have been built for testing, although not specifically designed to solve all issues, have been working quite satisfactorily for AC and DC currents up to 500 amps, and have been pressure tested up to 600 psi. The positive aspects of these designs will be applied to the ongoing study of feed-thru terminals as we work towards a solution.

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 2*

Title: **Thermal Control for Inverters and Motors**

Presenter: **John Hsu/Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 6

Relevance Rating (1-4): **2**

Relevance Justification: Very interesting technology with potential to make big technology impact. Speaker acknowledges barrier to automotive acceptance is very high.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Appears sound. Effort seems more empirical, not sure what fundamental science & technology is involved. I may not have fully understood approach.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: Behind the scenes of the laboratory work and results, our research involves the fundamental science and technology for refrigeration, heat transfer, coolant properties, mechanical stress considerations, etc. Fundamental studies of certain areas are also performed to help answer questions about results, and to help direct solutions to problems or barriers.

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: As an engineering effort, this project is "cool" (pun intended!). Progress appears to be as good as could be expected. Project results will be interesting contribution even if relevance is questionable.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 8*

Title: **Thermal Control for Inverters and Motors**

Presenter: **John Hsu/Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: The use of refrigerant cooling is a novel approach that is worth pursuing in some detail.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: This work could benefit dramatically from the longstanding experience in industry of refrigerant cooling of motors and more recently (last 10 years) inverters. It is surprising that there was not recognition of this large body of experience.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: We are closely tracking refrigerant cooled motors and inverter technologies. There are various technologies such as spray cooling, jet impingement cooling, submerged jet cooling, etc. that we are looking into. The uniqueness of the ORNL cooling technologies is utilizing the high pressure side of the AC system. Consequently unlike some existing technology using the cold side of the AC system, the ORNL coefficient of performance (COP) can reach 45 as compared with the 2-3 COP value of the AC system. The direct submerged cooling along with the geometry innovations are enabling very high power density with reduced silicon amounts and smaller dc link capacitor (reducing weight and cost). This design has presently proven 50% reduction in weight and 2x increase in power density. These improvements are partly due to the innovative design and choice of coolant and its source, but also due to known cooling capabilities of present technologies.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: This work would have made much better progress by starting with the substantial industry experience in refrigerant cooling.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Industry experience would have jump-started this work.

PI's Response to Technical Accomplishments Questions/Comments: The work was primarily enabled by the ORNL developed idea of using the high COP floating loop system. This idea is based on standard refrigerant cooling methods, but utilizes an available coolant source in the automobile that provides a very high COP.

Strengths: Innovative cooling approach.

Weaknesses: Lack of use of prior art.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 7***

Title: **Thermal Control for Inverters and Motors**

Presenter: **John Hsu/Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: GM commercialized a flourinert power electronics system - parallel hybrid truck - Have you asked GM about their experiences?

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: We are aware of GM's system and are pursuing more information on it.

Approach Rating (1-4): **3**

Approach Justification: Inverter is smaller but what about the size of the condenser? Is the condenser larger? What contamination effects have been noticed on the electronics? What is the leak rate for the vessel? What is the internal pressure of the vessel? Can non power devices be placed outside the vessel to limit fluid contact to just the devices that require cooling?

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: The condenser would be slightly larger in order to dissipate the heat; this is simply a trade-off for engine coolant radiator size, though, that would be required to be slightly larger to cool the traction drive as well. We have submerged the electronic components for 2+ years in refrigerant and have not detected any contamination of the electronics. The leak rate on the vessel depends on the current terminals. ORNL is currently addressing the need for high pressure and high current terminals to minimize the leak rate. Internal pressure on the vessel is the same as the high side pressure of the AC system (~150 PSI). For safety considerations, our design requirement was to withstand 500 PSI. Some of the non-power components can be placed outside the vessel because the vessel itself acts as a heat sink.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Interesting approach, lots of technical challenges. What are the potential failure modes - can a FMEA be performed?

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: Failure mode includes the short circuiting of the power switching devices and the capacitors, as in any power inverter. System coolant leakage is a failure mode, similar to an air conditioning system, and failure analysis can be performed in the same manner as is done for those designs. We have experienced some of these failures during normal development and testing situations, but these failures were not related to system design issues. The primary difference for this approach is the cooling environment, where the electronics are surrounded with the refrigerant - this is primarily a materials compatibility issue, and ongoing tests using standard components in refrigerant (>2 years) are showing no compatibility problems at all.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Title: **Thermal Control for Inverters and Motors**

Presenter: **John Hsu/Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **2**

Relevance Justification: While thermal management is important for the FreedomCAR program to meet its goals, it does not appear that this research project will substantially contribute to the knowledge base or assist in meeting the goals.

Potential to Meet Technical Target: No

If no, explain: See comment above.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **1**

Approach Justification: Work does not address the relevant issues for a systems approach or develop the knowledge needed to move toward meeting program goals. It is difficult to see there is real value being produced for the amount of investment in this project.

Approach sufficiently innovative: No
If no, explain: See comment above.

PI's Response to Approach Questions/Comments: There are tremendous cost and space savings by reducing the inverter size to half and further. From a systems level, the entire HEV traction drive system cooling requirement is being studied as a whole, with this single cooling method being utilized to remove all the heat from that system.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Some work has been accomplished but may not necessarily be relevant to program needs. Inverter design unlikely to be practical for automotive applications. Design presents challenges in getting power into and out of the container.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: ORNL recognizes that feed-thru terminals for high pressure/high current are an issue and are currently addressing this problem and working on a solution. The laboratory models that have been built for testing, although not specifically designed to solve all issues, have been working quite satisfactorily for AC and DC currents up to 500 amps, and have been pressure tested up to 600 psi. The positive aspects of these designs will be applied to the ongoing study of feed-thru terminals as we work towards a solution.

Strengths:

Weaknesses: Presentation was difficult to follow; did not flow logically.

Recommendations for Additions/Deletions to Project Scope: Recommend redirecting or canceling.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **Thermal Control for Inverters and Motors**

Presenter: **John Hsu/Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 2

Relevance Rating (1-4): **1**

Relevance Justification: Insufficient data that proposed technology can work when implemented in vehicle at temperatures at -40°C to 150°C.

Potential to Meet Technical Target: No

If no, explain:

PI's Response to Relevance Questions/Comments: The under hood temperature extremes are quoted to be -40°C to 140°C. The vessel is cooled by refrigerant that will buffer the operating temperatures for the actual electronics components. With proper terminal design the system will work properly at those temperatures.

Approach Rating (1-4): **1**

Approach Justification:

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient:

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 7*

Title: **Thermal Control for Inverters and Motors**

Presenter: **John Hsu/Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 7

Relevance Rating (1-4): **3**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: Quantify performance cost for right loop, addressing high pressure vessel containment pass throughs. What is temp and heat rejection capability of right loop?

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

The COP (Coefficient of Performance) for an AC system is known to be very low (COP~ 2-3). Our floating loop system DOES NOT REQUIRE THE COMPRESSOR to produce the required coolant. The floating loop is located on the high pressure side of the system and uses condenser temperature (~50-60ºC) refrigerant to remove the heat from the power electronics. There is only a small pump required in the floating loop side (right side) of the system to motivate the fluid flow in the correct direction. This means it draws very little power for electronics/motor cooling, and thus this system has achieved a COP ~ 45 for normal operation.

ORNL recognizes that feed-thru terminals for high pressure/high current are an issue and are currently addressing this problem and working on a solution. The ORNL laboratory models that have been built for testing, although not specifically designed to solve all issues, have been working quite satisfactorily for AC and DC currents up to 500 amps, and have been pressure tested up to 600 psi. The positive aspects of these designs will be applied to the ongoing study of feed-thru terminals as we work towards a solution.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Sufficient design work is complete to quantify cost and benefit. Report to Ken Kelly for comparison to other approaches.

Accomplishments Sufficient:

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 8*

Title: **Thermal Control for Inverters and Motors**

Presenter: **John Hsu/Curt Ayers** *Laboratory/Company:* **ORNL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **1**

Relevance Justification: Not addressing issues that would need to be taken care of before this idea would be successful. I/O issues addressed from high pressure vessel to outside world.

Potential to Meet Technical Target: No

If no, explain:

PI's Response to Relevance Questions/Comments: ORNL recognizes that feed-thru terminals for high pressure/high current are an issue and are currently addressing this problem and working on a solution. The ORNL laboratory models that have been built for testing, although not specifically designed to solve all issues, have been working quite satisfactorily for AC and DC currents up to 500 amps, and have been pressure tested up to 600 psi. The positive aspects of these designs will be applied to the ongoing study of feed-thru terminals as we work towards a solution.

Approach Rating (1-4): **1**

Approach Justification:

Approach sufficiently innovative: No

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year: Project is focused on only some of the issues.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 7***

Title: **Thermal Control for Inverters and Motors**

Presenter: **John Hsu/Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification: Use of direct cooling 2-phase approach using floating loop must be designed so as to rely as little as possible on proper functioning of the air conditioner, which is a notoriously poor reliability, high energy drawing component.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments: The COP (Coefficient of Performance) for an AC system is known to be very low (COP~ 2-3). Our floating loop system DOES NOT REQUIRE THE COMPRESSOR to produce the required coolant. The floating loop is located on the high pressure side of the system and uses condenser temperature (~50-60ºC) refrigerant to remove the heat from the power electronics. There is only a small pump required in the floating loop side (right side) of the system to motivate the fluid flow in the correct direction. This means it draws very little power for electronics/motor cooling, and thus this system has achieved a COP ~ 45 for normal operation.

Notoriously poor reliability is typically caused by leaking refrigerant (at the compressor shaft seal), and could be improved by using hermetically sealed motor/compressor systems (such as on 2004 Prius) and a leak proof high pressure/high current terminal along with warning systems indicating low refrigerant. It must also be remembered that the system does not require to be connected to the AC system but can operate as a stand-alone 2-phase coolant system.

Approach Rating (1-4): **3**

Approach Justification: Good design approach for 1/2 size inverter, good motor cooling approach. Overall concept of reducing size through the use of direct 2-phase cooling (using floating loop approach) must limit reliance on air conditioner as discussed in #1.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Excellent progress on 1/2 size inverter design. Interesting new motor cooling approach. Progress in isolating cooling from air conditioner.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Motor cooling approach. Smaller inverter design.

Weaknesses: Any reliance on proper functioning of air conditioner.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 8***

Title: **Thermal Control for Inverters and Motors**

Presenter: **John Hsu/Curt Ayers** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: This project is highly relevant to the goals of increasing power density and reliability.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: It seems that the project is a bit overdriven. There are various fundamental issues and assumptions that have only been treated superficially. For ex., the compatibility of fluid and packaging, heat transfer performance, & stability, orientation dependence. However, clearly a balance has been struck to please several stakeholders.

Approach sufficiently innovative: Yes

If no, explain: Although commercial application was mentioned, I have not seen an implementation like this in the academic industry or patent literature (yet). I suspect the commercial application is for much lower power density.

PI's Response to Approach Questions/Comments: We have looked into various issues addressed in this concern. Last year we investigated refrigerant properties in great depth and the results are detailed in our ORNL-TM-2005-219 report. The packaging and heat transfer performance tests are ongoing for this project. We have reported on these results in previous presentations. Over the past 2 years we have been submersion testing standard components/boards in R134a with no degradation whatsoever detected. The orientation of the inverter was considered to meet all of the practical tilt angles of the vehicle. The design of this one embodiment can handle a high angle of tilt without coolant problems. All possible embodiments for this have not been studied, but there are no problems anticipated with the proposed design.

We have been granted patents on this technology by the U.S. Patient Office and there are also ongoing patents pending. Our inverter design is for very high power density, which is a combination of innovative packaging and geometry, enabled by the direct cooling method. Liquid and/or 2 phase cooling is not a new concept for electronics cooling, but our design is an attempt with the new geometry to radically increase the power density as compared for example to the Semikron inverter.

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: My impression is that a great deal of useful work has been accomplished. The prototype performance is very promising. I would like to see some fundamental studies that would improve understanding of thermal management system and increase confidence in its performance.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Prototype exhibits excellent power density, potentially innovative 2-phase cooling system.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: Fundamental thermal-fluids studies. Chemistry analysis, R134a w/all circuit components. Serviceability.

Additional Comments: It was very difficult to understand first presenter. Recommend other….

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 8***

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Please see the ORNL-TM-2005-219 report for refrigerant/coolant properties. The thermal and heat transfer issues are still being studied, with very respectable heat flux numbers being proven. Compatibility issues were covered above. Serviceability of this type of system is already an industry standard, with mechanics very familiar with servicing standard auto AC systems (R134a service equipment). This application only adds the requirement of being able to diagnose and remove/replace electronics components as is already done on numerous other parts of the typical automobile.

Reviewer Affiliation: Industry | ***Reviewer's Ability to Rate (1-10): 9***

Title: **Uncluttered CVT Machines**

Presenter: **John Hsu** | ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **2**

Relevance Justification: This work appears to miss the target of cost effectiveness which is key to the success of the Freedom Car work.

Potential to Meet Technical Target: No

If no, explain: Appears to be high cost inherently.

PI's Response to Relevance Questions/Comments: The objective is to utilize the counter torque of the rotating stator to harvest a doubling of torque at a given speed of the rotating components. This design adds an additional elector-magnetic coupling through the two rotating components. This provides an additional level of flexibility for CVT designed machines.

The design combines the motor and generator and CVT into one module and completely eliminates the need for one set of permanent magnets. Having the capability to harvest twice the amount of torque for a given motor size, the motors can be manufactured smaller with a higher torque density. This approach will result less materials and a tremendous cost savings in manufacturing.

Approach Rating (1-4): **2**

Approach Justification: Added complexity does not appear to offer promise for success.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Until designs are completed showing expected performance, optimism should be tempered.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Just a concept for now.

PI's Response to Technical Accomplishments Questions/Comments: The rotor along with its half stator were fabricated and successfully tested this year, which proved the concept. This hardware verification test was a milestone necessary to validate the torque coupling mechanism necessary for the design to be successful. Additional testing results will be available in the Annual Report. Based upon these tests the concept was proven and the remainder of the machine will be constructed next FY.

Strengths: Innovative.

Weaknesses: Complex and likely high cost, low reliability.

Recommendations for Additions/Deletions to Project Scope: Consider complexity costs of real designs.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Obtaining the aggressive FCVT reliability targets is an issue with any design we undertake. We will be assessing these goals as the project progresses.

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 10***

Title: **Uncluttered CVT Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Combining machine and gearing is a very good step forward. Today HEV, and perhaps PHEV propulsion drives rely strongly on electric machines combined with planetary gears.

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Doing the dual rotor prototype (no windings) first to validate rotor magnetics makes solid approach.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Still concerned with the magnetic performance of the PM to uncluttered rotor performance. We are at the stage on this one where some experimental evidence will go a long way.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: We are at a very early stage in this project. Please see the annual report for the uncluttered rotor proof of concept test results

Strengths: PI has very solid grasp of electro-mechanical and magnetic essentials of CVT.

Weaknesses: Machine concept is a stretch and poses risk but rewards could pan out.

Recommendations for Additions/Deletions to Project Scope: Need to see validation data.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 8***

Title: **Uncluttered CVT Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 3

Relevance Rating (1-4): **2**

Relevance Justification: No design and simulation data to justify the project and goals (slide 2).

Potential to Meet Technical Target: No

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **2**

Approach Justification: Lack of data.

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments: This motor is still in the development stage. Validation data will be available after initial testing is completed. Please see the Annual report for additional information.

Technical Accomplishment and Progress Rating (1-4): **1**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **Uncluttered CVT Machines**

Presenter: **John Hsu** *Laboratory/Company:* **ORNL**

Research is Important to FreedomCAR (1-10): 2

Relevance Rating (1-4): **1**

Relevance Justification: While the project may be innovative it is likely to be impractical for application in most automotive applications. Each OEM is likely to want to determine its own systems approach to motors and transmissions.

Potential to Meet Technical Target: No

If no, explain: It is not clear what target is being addressed by this technology. It provides a system that is not aligned with the specific goals.

PI's Response to Relevance Questions/Comments: The objective is to utilize the counter torque of the rotating stator to harvest double the torque at a given speed of the rotating components. This adds an additional electro-magnetic coupling through the two rotating components. This provides more flexibility for CVT design.

Specific targets were peak power to weight ratio (kW/kg) of >1.3, peak power to volume ratio (kw/l) of >3.5, cost ($/pk kW) of <$11, efficiency of >91 and lifetime of 15 years. The impacts of this project were to combine the motor and generator in one unit, decreasing system size, volume, weight and costs. The unique design provides for increased torque coupling between rotors while needing only one permanent magnet rotor for the entire motor/generator. This will significantly lower the costs of the system.

Approach Rating (1-4): **1**

Approach Justification: No data and results are provided to substantiate the claims of success in the presentation. Too little information is shared to account for $600K+ spent over the year. It appears it is taking too long to produce hardware.

Approach sufficiently innovative: No
If no, explain: It may be innovative but it is irrelevant to the needs of most OEMs.

PI's Response to Approach Questions/Comments: This machine is not a conventional design but is based on a totally new concept. There are considerable design challenges that must be addressed prior to producing hardware.

Hardware was produced this year. The uncluttered rotor along with its half stator were fabricated, assembled and successfully tested to prove the flux coupling concept The remainder of the build will occur next year.

Please see the Annual Report for test results and further testing data.

Technical Accomplishment and Progress Rating (1-4): **1**

Technical Accomplishment and Progress Justification: The amount of information and technical data is severely lacking especially when compared to the amount of data and information shared by other PIs in similar areas of research. Question the value in the overall design concept -- integrating the motor with a CVT may not be an optimal design approach for all vehicle applications. Is DOE getting sufficient value for its money?

Accomplishments Sufficient: No

Significant Accomplishments During Year: Taking too long to produce hardware, assuming that there is agreement that developing hardware is justified.

PI's Response to Technical Accomplishments Questions/Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 5***

Strengths: There is too little concrete information provided to be able to identify strengths.

Weaknesses: Presentation too superficial; no data is provided to be able to evaluate project. It is unclear how the $600+ was spent during the year. There are no results shown to justify the level of expenditures. No data. No information. Too superficial. Where is the engineering analysis?

Recommendations for Additions/Deletions to Project Scope: More data and engineering analytical results need to be shared by the PI to justify continued expenditures.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: A total of 12 design iterations were considered and each design was analyzed in Pro/E Mechanica, Comsol, AnSoft and AnSYS for electro-magnetic results as well as mechanical component stress before the optimum design was chosen. The uncluttered rotor along with its half stator were fabricated, assembled and successfully tested to prove the concept works. Please see the Annual Report for test results and further testing data.

Reviewer Affiliation: OEM **Reviewer's Ability to Rate (1-10): 5**

Title: **Uncluttered CVT Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **2**

Relevance Justification: I have not seen how the Complexity of this architecture can beat the low cost of a simple gear reduction system. Please estimate the benefits in a comprehensive way.

Potential to Meet Technical Target: No

If no, explain: Can't tell from information presented.

PI's Response to Relevance Questions/Comments: We are in the early stages of this project. The objective of this effort is to utilize the counter torque of the rotating stator to double the motors torque. The concept adds an additional elector-magnetic coupling through the two rotating components. This provides more flexible possibilities for CVT design. Having the capability to harvest twice the amount of torque for a given motor size, the motors can be manufactured smaller with a higher torque density. This design combines the motor, generator, and CVT into one module which requires half the amount of permanent magnet material. This approach will result in a tremendous cost savings in manufacturing and should also simplify the power electronics resulting in cost savings in that unit as well.

Approach Rating (1-4): **2**

Approach Justification: Performance metrics for the system (e.g., eff., cost….) should be determined and communicated in the workplan so we can see the progress made for each stage of the project).

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: We are in the early stages of this project. As the project progresses we will be reporting on the progress.

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: I would love to see more objective measures of progress and design direction communicated (i.e. successful tests need to be quantified - how successful?).

Accomplishments Sufficient: No

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments: See comment above.

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope: What are the power electronics needs and implications of this complex machine?

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: Both the motor and generator will require individual inverters. The rating on the inverters will be lower than those in traditional HEV topologies because both sides can act together to produce torque.

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 6***

Title: **Uncluttered CVT Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification: We don't seem to be getting to any really complete sets of data/analysis.

Potential to Meet Technical Target:

If no, explain:

PI's Response to Relevance Questions/Comments: This project is just getting underway this year. We successfully proved the concept of flux coupling necessary for this design to be successful with simulations and hardware built this FY. Please see the annual report for the uncluttered rotor proof of concept test results.

Approach Rating (1-4): **2**

Approach Justification:

Approach sufficiently innovative:
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **1**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient:

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 7***

Title: **Uncluttered CVT Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Incorporating CVT with PM motors to double torque output.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Rotating stator to double torque production is quite interesting idea.

Approach sufficiently innovative: Yes
If no, explain: It's unconventional approach.

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **2**

Technical Accomplishment and Progress Justification: Only conceptual analysis is done.

Accomplishments Sufficient: No

Significant Accomplishments During Year: It's difficult to prove concept in a short time period.

PI's Response to Technical Accomplishments Questions/Comments: This project is just getting underway. However, the rotor along with its half stator were fabricated and successfully tested which proved the concept of flux coupling necessary for the success of this project works. Additional testing results will be available in the Annual Report.

Strengths: Design from system level to improve motor performance.

Weaknesses: unconventional design, difficult to prove.

Recommendations for Additions/Deletions to Project Scope: 1. Need to have hardware model. 2. Need to have control and electronics in the scope.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D ***Reviewer's Ability to Rate (1-10): 2***

Title: **Uncluttered CVT Machines**

Presenter: **John Hsu** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **3**

Relevance Justification: CVT machines have great promise for improving energy efficiency and thus for meeting FreedomCAR system goals. The idea of harvesting energy back from the stator by using the motor as a generator is very good for meeting power/volume and power/weight goals at the system level.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Very innovative way to recapture energy from rotating motor converter torque.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Design, prototyping, and initial testing are complete.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Wide Bandgap Materials**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: WBG (SiC especially) fundamental to reducing system cost by using high temp cooling. Only realistic path to air cooling.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: The key elements are needed and a contribution may be overly reliant on sampling of components, i.e., no proactive development of WBG components. Perhaps new RFP will rectify this.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Lots of progress in a multifaceted effort.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Evaluation & modeling of WBG components. Thermal analysis.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 9***

Title: **Wide Bandgap Materials**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: High need for 200-225º C operation.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Progressing in small steps is good engineering practice to fully understand implications of packaging and control interactions.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Have experimental inverter operating under real world AC-drive conditions.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Good team and I'm pleased to see use of GaN.

Weaknesses: Harnessing benefits of HT electronics when all supporting components are low temp.

Recommendations for Additions/Deletions to Project Scope: Need to hear more about how these HT components will be integrated into a system.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: The under the hood temperatures are expected to be around 140C; therefore, the FreedomCAR program is funding research on high temperature devices and supporting components. We are expecting that when the high temperature SiC power devices are ready, high temperature capacitors and gate drivers will also be ready for system integration.

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 5*

Title: **Wide Bandgap Materials**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: High temp tolerance is essential to achieving FreedomCAR goals, and to making these systems reliable without expensive cooling.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Logical approach to pull ahead thermal packaging and inverter modeling, since SiC switching devices aren't readily available.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: Good use of available devices and demonstration of device capabilities through test (SiC diodes).

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Compared different power electronics types through simulation.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry *Reviewer's Ability to Rate (1-10): 5*

Title: **Wide Bandgap Materials**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **3**

Relevance Justification: The ability to run at higher temperatures is important to meeting the packaging and cost requirements. This would include the cost of the cooling system as well.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Teaming with industry sources and looking at novel combinations of Si and SiC based systems seems to be a reasonable approach.

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Modeling results are encouraging. It would be interesting to see how well the test results match the models.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Reasonable approach, combination of practical and novel.

Weaknesses: Need to continue to work on the cost aspect (including yield) for SiC devices.

Recommendations for Additions/Deletions to Project Scope: Need to continue to work on the cost aspect (including yield) for SiC devices.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: Industry ***Reviewer's Ability to Rate (1-10): 6***

Title: **Wide Bandgap Materials**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **3**

Relevance Justification: Cost is an issue.

Potential to Meet Technical Target: Yes

If no, explain: If cost for SiC drops.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: The comparisons to Si and hybrid Si inverters were very good. One of the stated goals was to increase power density to reduce silicon size. Has any work been done to understand what limits Si power density? i.e. at a given junction temperature (do not exceed junction temperature) what limits the amount of current the Si device can handle at 20 kHz switching into an inductive load? What is the failure mode?
When you parallel higher current SiC devices, have you looked at how well the devices share current at the instant of switch turn on? IR images would be interesting.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments: In this case, for a given junction temperature, the device losses will limit the operation of the device. Si devices have higher conduction and switching losses, which are functions of the material and device properties. As the heat builds up, the device would burn open without proper protection.

We have not looked at current sharing. We agree with the reviewer the IR images might be IR images might be interesting. We will look into this.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Lots of simulations, need to see more actual data. Would like to see more details on the implementation of the thermal path.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **Wide Bandgap Materials**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification: Power electronics that can meet the cost and temperature tolerance goals of the FreedomCAR program are critical to the success of the program and for OEMs to be able to offer HEVs that are affordable and can meet customer needs.

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification: Good work is being done by the PI but needs to do even more. Pleased to see that the PI is concentrating on testing and analyzing hardware procured from suppliers rather than spending time/resources on in-house design and build of hardware to be tested.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification: One of the best projects reported at the APEEM review this year. Good results and progress. Need to do more!

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Good analysis. Good report. Thorough presentation with good and relevant information pertinent to the program and providing valuable information for the reviewers.

Weaknesses: Need to double check the accuracy of efficiency data provided on bottom of page 9.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: The important point of the efficiency plots in the presentation was to compare the efficiencies of the two inverters at the same conditions. We have operated the Si and Si-SiC hybrid inverters in many different conditions and we have other plots showing high efficiencies (>97%) of Si and even higher efficiencies of Si-SiC hybrid inverter. We will present our high efficiency results in the annual report. We believe the data we presented is accurate.

Reviewer Affiliation: OEM *Reviewer's Ability to Rate (1-10): 5*

Title: **Wide Bandgap Materials**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 8

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM

Reviewer's Ability to Rate (1-10): 6

Title: **Wide Bandgap Materials**

Presenter: **Burak Ozpineci**

Laboratory/Company: **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: OEM ***Reviewer's Ability to Rate (1-10): 8***

Title: **Wide Bandgap Materials**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 10

Relevance Rating (1-4): **4**

Relevance Justification:

Potential to Meet Technical Target: Yes

If no, explain:

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **4**

Approach Justification:

Approach sufficiently innovative: Yes

If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **4**

Technical Accomplishment and Progress Justification:

Accomplishments Sufficient: Yes

Significant Accomplishments During Year:

PI's Response to Technical Accomplishments Questions/Comments:

Strengths:

Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10): 10*

Title: **Wide Bandgap Materials**

Presenter: **Burak Ozpineci** *Laboratory/Company:* **ORNL**

Research is Important to FreedomCAR (1-10): 5

Relevance Rating (1-4): **2**

Relevance Justification: 1. SiC material is good for high temperature, but it's positive temperature coefficient can easily cause thermal runaway. 2. Wide bandgap has high junction voltage which results in high voltage drop, increasing conduction loss. 3. SiC should be aimed for higher voltage systems such as 2 kV or higher.

Potential to Meet Technical Target: No

If no, explain: I have developed SiC inverters and tested devices substantially. No promising results were found. I do see potential with SiC diodes at 50 V and above. Their voltage drop is much less than Si counterpart.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Perhaps due to design issue, the presented information is quite different from state-of-the-art. Efficiencies of Si inverter is far inferior to what we have seen in typical designs.

Approach sufficiently innovative: No
If no, explain: Innovation will be in SiC device itself and possibly package.

PI's Response to Approach Questions/Comments: The important point of the efficiency plots in the presentation was to compare the efficiencies of the two inverters at the same conditions. We have operated the Si and Si-SiC hybrid inverters in many different conditions and we have other plots showing high efficiencies (>97%) of Si and even higher efficiencies of Si-SiC hybrid inverter. We will present our high efficiency results in the annual report.

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Some real numbers have been attained although they are somewhat questionable and controversial.

Accomplishments Sufficient: No

Significant Accomplishments During Year: Need design optimization and fair comparison between Si and SiC devices.

PI's Response to Technical Accomplishments Questions/Comments: We feel the comparisons presented are fair. All the Si and SiC devices have been tested on the same system at the same conditions. At some instances, we have pushed SiC devices to operate at harsher conditions since they can handle it.

Strengths: Evaluation of SiC with mathematical models.

Weaknesses: Foundation of tested results is weak, not agree with the analytical results.

Recommendations for Additions/Deletions to Project Scope:

Additional Comments: SiC is a new material. Performance may or may not exceed Si counterpart. It is not necessary to stress it's superiority but just to show its potential should be good enough. Typically 1% improvement in efficiency is significant when overall efficiency is above 95% pure device improvement may achieve 1% improvement but not a dramatic 4% that's reported in the presentation.

PI's Response to Strengths, Weaknesses, Recommendations, and Comments: The presentation showed the simulation results we have obtained in our simulation. Comparing the single device performances, we believe that the results are accurate. Please note that we have made assumptions to predict the performances of the full-power inverters using models of low power devices.

Reviewer Affiliation: R&D *Reviewer's Ability to Rate (1-10):* *10*

Title: **Wide Bandgap Materials**

Presenter: **Burak Ozpineci** ***Laboratory/Company:*** **ORNL**

Research is Important to FreedomCAR (1-10): 9

Relevance Rating (1-4): **4**

Relevance Justification: Definitely a high risk, long-range program with high payoff. SiC devices are just now becoming commercially available (diodes and VJFETS and then successful incorporation into inverters/converters shows great promise, but requires clear understanding of requires clear understanding of the characteristics of the SiC.

Potential to Meet Technical Target: Yes

If no, explain: Project shows goals significantly exceed FreedomCAR goals. The risk, however, SiC is unproven technology.

PI's Response to Relevance Questions/Comments:

Approach Rating (1-4): **3**

Approach Justification: Good approach - Device characterization then inverter model, then assemble into inverter then packaging and test. More fundamental understanding of packaging device performance/reliability interaction needed.

Approach sufficiently innovative: Yes
If no, explain:

PI's Response to Approach Questions/Comments:

Technical Accomplishment and Progress Rating (1-4): **3**

Technical Accomplishment and Progress Justification: Good characterization of SiC . JFETs and of SiC vs GaN diodes. Excellent simulation of inverter efficiency and heat management improvement of SiC over Si or Si-SiC hybrid. More work needed on packaging and reliability to optimize inverter - still test prototype in this area. Reviewer question pointed out the need for additional thermal cycling, thermal shock characterization of reliability.

Accomplishments Sufficient: Yes

Significant Accomplishments During Year: Characterization of SiC diodes and JFETS. Simulation of inverter efficiency and thermal improvement. Needed to move forward with program and prototype.

PI's Response to Technical Accomplishments Questions/Comments:

Strengths: Clearly demonstrates maturity of SiC (GaN) devices. Clearly demonstrates advantages of full SiC approach.

Weaknesses: Need additional work on packaging - device interaction. Need additional packaging improvements in density, thermal, and reliability.

Recommendations for Additions/Deletions to Project Scope: Development of full high temperature, high reliability package that provides high power density, integrated inverter for demonstration instead of just test packaging.

Additional Comments:

PI's Response to Strengths, Weaknesses, Recommendations, and Comments:

Appendix F – Results of the Questionnaire for Evaluating the Peer Review Process

FreedomCAR and Vehicle Technologies Annual Review of
Power Electronics and Electric Machines
August 15-17, 2006
Pollard Technology Conference Center, Oak Ridge, TN
DOE Office of Energy Efficiency and Renewable Energy
Questionnaire for Evaluating the Peer Review Process

Twenty questionnaires returned and listed as 1–20 in results.

A. Demographic Questions

A-1. What was your role in the review?

Peer Reviewer 5
[ANSWER ONLY SECTIONS B & C]

Presenter of a program activity or project under review (non-program office presenter) 5
[ANSWER ONLY SECTIONS B & D]

Presenter of a program activity or project under review (program office staff) 2
[ANSWER ONLY SECTIONS B & D]

Attendee, neither Reviewer nor Presenter..7
[ANSWER ONLY SECTION B]

Unspecified..1

A-2 What is your affiliation?

Government agency directly sponsoring the program under review 0
National/government lab, private-sector or university researcher whose project is under review 7
In an industry directly involved in the program under review 1
In an industry with interest in the work under review 7
Government agency with interest in the work 1
National/government lab, private-sector or university researcher not being reviewed, but
who has an interest in the work 1
Other (please specify, e.g., consultant, retired employee, public, etc.) 1
(9) Government employee in technical support role to S. Rogers, DOE.
Unspecified 2

B. QUESTIONS B-1 THROUGH B-14 FOR ALL ATTENDEES

B-1	Purpose and scope of review were well defined.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 0; 4 = 6; 5 = 14
B-2	The quality, breadth, and depth of the following were sufficient to contribute to a well-considered review:	*disagree* *agree* *1 2 3 4 5*
	1. Presentations.	1 = 0; 2 = 0; 3 = 2; 4 = 10; 5 = 8
	2. Question & Answer periods.	1 = 0; 2 = 0; 3 = 0; 4 = 9; 5 = 11
	3. Answers provided concerning programmatic questions.	1 = 0; 2 = 0; 3 = 1; 4 = 8; 5 = 11
	4. Answers provided concerning technical questions	1 = 0; 2 = 0; 3 = 2; 4 = 10; 5 = 8
B-3	Enough time was allocated for presentations.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 2; 4 = 7; 5 = 11
B-4	Time allowed for the Question & Answer period following the presentations was adequate for a rigorous exchange.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 1; 4 = 5; 5 = 14
B-5	The questions asked by reviewers were sufficiently rigorous and detailed.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 7; 4 = 8; 5 = 5

B-6 What questions should have been asked but were not?

(1) Questions aimed at directing future research focus seemed absent compared to previous reviews.

(2) At certain point in time, should ORNL arrange a system integration project that will pull all the good works together? It will add values to the APEEM program and individual works.

(3) Is there an opportunity for reconsideration of 40 mile range for PHEV; i.e., this probably should be about 2x (~100 miles) for coverage of most commuters?

If PHEV is to become a major part of PEEM, some integration of battery program (USABC) should be started. Ultra-capacitors also should be part of the options considered for full PHEV and HEV, i.e. a peak power source.

How are generators or recharge capabilities integrated with drive motor system?

(4) All presenters tried to comply with the spec., but it's still a big question about the temperature goal. It seems to conflict with the cost target and no sign of achieving the goal, at least in the next five years.

(5) One question was asked about fault tolerance. However, there should probably be more emphasis on motor design, controller design, and system design for fault tolerance.

- How to avoid faults.
- How to have graceful failure modes or shut downs if faults occur (no damage to components).
- Define all known drive system faults.
- Reduce occurrence thru design.

Improve failure modes thru design.

(6) The projects are somewhat open ended. Have a well defined set of performance targets but not a specific class of vehicle to base packaging targets to.

(7) When will other OEM's release for sale a Prius equivalent?

(8) Is the balance of work between motors/electronics/batteries understood within the DOE and labs? Is funding aligned with the challenges?

(9) It would be beneficial to have more interactive comments from the OEM's during the questions and answer periods.

B-7	There were no problems with:	*disagree* *agree*
	1. Classification of projects (project groupings)	1 = 0; 2 = 0; 3 = 0; 4 = 5; 5 = 15 *N/A* = 0
	2. Quality/level of the information presented	1 = 0; 2 = 0; 3 = 2; 4 = 10; 5 = 8 *N/A* = 0
	3. Proprietary data	1 = 0; 2 = 0; 3 = 2; 4 = 6; 5 = 9* *N/A* = 3
	*(12) Project background data should have been supplied in advanced to the reviewers. Better descriptions were needed for novel geometries, e.g., Hsu's odd motors.	
B-8	The frequency *(insert the planned frequency of review – e.g., annual, biennial, etc.)* of this kind of formal review process for this program/subprogram is:	About right = 18 Too frequent = 0 Not frequent enough = 1*
	*(13) Should have two meetings per year – seems to be slipping to one meeting per year.	
B-9	The review was conducted smoothly.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 0; 4 = 2; 5 = 17

B-10 What was the most useful part of the review process?

(1) The consistent presentation template was helpful.

(2) Question and answer.

(3) Care was obvious to ensure audience understood role of projects in overall program.

(4) Question and answer.

Presentations are generally well organized for review purpose.

(5) Sharing of information across programs.

(6) Getting program updates.

(7) Power electric development and thermal efforts capacitors for higher voltages may benefit from some of the current efforts.

Networking with other lab POC and industry OEM's.

(8) Technical content – more data that is apples-to-apples so that the technology can assessed.

(9) The presentations and follow on discussions were beneficial. The interactive lunches and breaks allowed for an excellent interface with the presenters and reviewers.

(10) Networking with others involved in the Power Electronics program.

(11) Questions asked right after the presentations. Also, just interacting with various people during the course of the review meeting.

(12) a–Q&A at the end of each presentation.

b–Chance for one-on-one Q&A at lunch or break.

(13) Very good structure – the introduction presentations were excellent. The project presentations were well done, extensive time permitted for Q&A and off-line discussion with presenters.

(14) One-on-one instructions during breaks and lunch.

(15) Questions and answers/dialogue between technical experts in audience and the PI.

(16) Clear identification of the program goals.

(18) The question and answer sessions and the panel sessions.

(20) Interaction with industrial people.

B-11 What could have been done better?

(2) Well done.

(3) Maybe an "experts" workshop could be run at night or later afternoon to allow in depth exchange of technical progress.

(4) Size of fonts need to be large enough for audience to read well.

(5) Good review for combined program management and technical.

Could a pure technical review with more detail be useful?

(6) I'd prefer to see more of the project schedules.

(7) Possibly some discussion on how integration of the different tech developments would be integrated into an overall system.

(8) Technical content – more data that is apples-to-apples so that the technology can be assessed.

(9) For the presentations, dimmed lights on stage so visual pictures would be seen better.

Since the programmatic information was not suitable for all the presentations. There should be some flexibility in the format.

(10) Is there/should there be a forum for communicating/updating materials throughout the year.

(12) Advanced delivery of background material to reviewers.

(13) Reviewer deliberation sessions between topics to permit additional brainstorming and discussion between reviewers – perhaps this could be part of the end of the session panel discussion.

(15) Need to continuously remind person asking questions to identify himself and speak loudly and clearly.

(18) Providing more technical details in the presentations.

B-12	Overall, how satisfied are you with the review process?	*very unsatisfied* 1 = 0; 2 = 0; 3 = 1;	*very satisfied* 4 = 6 5 = 13
B-13	Would you recommend this review process to others and should it be applied to similar DOE programs?	*Yes* = 20	*No* = 0

B-14. Please provide comments and recommendations on the overall review process.

(1) It would be helpful to understand how new programs are proposed and approved, e.g. the new switchable winding motor program for FY07.

(2) Well done.

(3) Maybe an "experts" workshop could be run at night or later afternoon to allow in depth exchange of technical progress.

(4) Reviewers need a table to work more comfortably and to write more legibly.

(5) Very well organized and structured.

(6) The presentation format is a good blend of program and technical content.

(7) Thought the views were informative in identifying and addressing the plan to build FS-cars in 2020.

Not sure why more emphasis is not on FS-cars. Some industry already makes a HEV. Benefits will be gained from the HEV and plug-ins, but different problems will need to be addressed once you fully address FC-cars.

(8) More technical content.

(9) It would be good to have the questions from the audience repeated by either the session chairman or presenter so everyone could clearly hear the questions asked.

(10) Is there/should there be a forum for communicating/updating materials throughout the year.

(11) Overall, it was a very useful meeting.

(12) Project background data should have been supplied in advanced to the reviewers.
Better descriptions were needed for novel geometries, e.g., Hsu's odd motors.

(13) Answers to B-2(1), B-3, and B-7(2) related to the fact that too much of the presentation is devoted to programmatic issues and not enough for technical, leading to many clarification questions on technical background and detail. Need additional slides on technical background for each presentation or for introductions explaining (in technical detail) the limitations and why the chosen presentations will solve them.

The "goals" slide showing where the R&D goals were in relation to the FreedomCAR goals was very nice. However, in addition, it would be nice to know why certain limitations were identified as being the key problems (FreedomCAR road map, so to speak) and why these programs were chosen to address them. Also, for those projects where the R&D goals are significantly below the FreedomCAR goals, the approach to address these shortcomings should be explained and emphasized. NREL should also have this "goals" slide, it was missing form their presentations.

More technical detail is essential – some presentations asserted the completion of tasks with no data to back it up.

(14) It would be very helpful to have an attendees list for the meeting. It helps the presenters understand the audience.

(15) Good review. Keeps getting better every year.

Well organized. Kept on time.

(16) The FOM is referenced to the peak power. However, many of the designs are controlled by the continuous power. Suggest using continuous power for the FOM.

System trades between competing strategies seems to just be starting. I look forward to more detailed/complete understanding between trades in the future.

(20) Some projects may need a longer presentation time, say 30 minutes.

C. QUESTIONS C-1 THROUGH C-12 FOR PEER REVIEWERS ONLY

C-1	Information about the program/subprogram /projects under review was provided sufficiently prior to the review session.	*disagree* *agree* 1 = 0; 2 = 1; 3 = 0; 4 = 1; 5 = 3
C-2	Review instructions were provided in a timely manner.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 0; 4 = 1; 5 = 4
C-3	The information provided in the presentations was adequate for a meaningful review of the projects.	*disagree* *agree* 1 = 0; 2 = 1; 3 = 1; 4 = 0; 5 = 2
C-4	The evaluation criteria upon which the review was organized were clearly defined and used appropriately.	*disagree* *agree* *1 2 3 4 5*
	1. Quality, Productivity, Accomplishments	1 = 0; 2 = 0; 3 = 0; 4 = 3; 5 = 2
	2. Relevance	1 = 0; 2 = 0; 3 = 0; 4 = 3; 5 = 2
	3. Management	1 = 0; 2 = 0; 3 = 1; 4 = 3; 5 = 1
	4. Other (1):	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
	5. Other (2):	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
C-5	Explanation of the questions within the criteria was clear and sufficient.	*disagree* *agree* *1 2 3 4 5*
	1. Quality, Productivity, Accomplishments	1 = 0; 2 = 0; 3 = 0; 4 = 2; 5 = 3
	2. Relevance	1 = 0; 2 = 0; 3 = 0; 4 = 2; 5 = 3
	3. Management	1 = 0; 2 = 0; 3 = 0; 4 = 2; 5 = 3
	4. Other (1):	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
	5. Other (2):	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
C-6	The right criteria were used to evaluate the project(s)/program.	*disagree* *agree* *1 2 3 4 5*
	1. Quality, Productivity, Accomplishments	1 = 0; 2 = 0; 3 = 0; 4 = 3; 5 = 2
	2. Relevance	1 = 0; 2 = 0; 3 = 0; 4 = 3; 5 = 2
	3. Management	1 = 0; 2 = 0; 3 = 0; 4 = 3; 5 = 2
	4. Other (1):	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
	5. Other (2):	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
C-7	During the review process, reviewers had adequate access to principle investigators, research staff, or requested sources of additional data.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 0; 4 = 2; 5 = 3
C-8	The number of projects I was expected to review was	*disagree* *agree* *1 2 3 4 5*
	a. Too many	1 = 0; 2 = 1; 3 = 1; 4 = 0; 5 = 1
	b. Too few	1 = 1; 2 = 1; 3 = 0; 4 = 0; 5 = 0
	c. About right	1 = 0; 2 = 0; 3 = 0; 4 = 2; 5 = 2
C-9	The reviewers in my session had the proper mix and depth of credentials for the purpose of the review. *(12) No distinct reviewers by sessions was seen.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 0; 4 = 3; 5 = 1 *Don't know their credentials* = 1*
C-10	There were no problems with the numerical rating schemes used.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 0; 4 = 4; 5 = 1 *N/A* = 0
C-11	Altogether, the preparatory materials, presentations, and the Question & Answer period provided sufficient depth of review. *(12) Preparatory materials – None.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 1*; 4 = 3; 5 = 1
C-12	When considering the final reporting of recommendations:	*disagree* *agree*
	1. Process for developing final reporting was appropriate.	1 = 0; 2 = 0; 3 = 1; 4 = 4; 5 = 0 *N/A* = 0
	2. Enough time was allocated for reviewers to deliberate before recording review comments.	1 = 0; 2 = 1; 3 = 2; 4 = 2; 5 = 0 *N/A* = 0

D. QUESTIONS D-1 THRU D-9 FOR PRESENTERS ONLY

D-1	The request to provide a presentation for the review was made sufficiently prior to the deadline for submission.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 1; 4 = 0; 5 = 6
D-2	Instructions for preparing the presentation were sufficient.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 0; 4 = 3; 5 = 4
D-3	The evaluation criteria upon which the review was organized were clearly defined and used appropriately.	*disagree* *agree* *1 2 3 4 5*
	1. Quality, Productivity, Accomplishments	1 = 0; 2 = 0; 3 = 0; 4 = 2; 5 = 4
	2. Relevance	1 = 0; 2 = 0; 3 = 1; 4 = 2; 5 = 3
	3. Management	1 = 0; 2 = 0; 3 = 0; 4 = 3; 5 = 3
	4. Other (1):	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
	5. Other (2):	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
D-4	Explanation of the questions within the criteria was clear and sufficient.	*disagree* *agree* *1 2 3 4 5*
	1. Quality, Productivity, Accomplishments	1 = 0; 2 = 0; 3 = 0; 4 = 1; 5 = 3
	2. Relevance	1 = 0; 2 = 0; 3 = 0; 4 = 1; 5 = 3
	3. Management	1 = 0; 2 = 0; 3 = 0; 4 = 1; 5 = 3
	4. Other (1):	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
	5. Other (2):	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
D-5	The right criteria were used to evaluate the project(s)/program.	*disagree* *agree* *1 2 3 4 5*
	1. Quality, Productivity, Accomplishments	1 = 0; 2 = 0; 3 = 0; 4 = 1; 5 = 3
	2. Relevance	1 = 0; 2 = 0; 3 = 0; 4 = 1; 5 = 3
	3. Management	1 = 0; 2 = 0; 3 = 0; 4 = 1; 5 = 2
	4. Other (1): (10) Solicit constructive comments directly.	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
	5. Other (2):	1 = 0; 2 = 0; 3 = 0; 4 = 0; 5 = 0
D-6	During the review process, reviewers had adequate access to principle investigators, research staff, or requested sources of additional data.	*disagree* *agree* 1 = 0; 2 = 1; 3 = 0; 4 = 2; 5 = 3
D-7	The reviewers in my session had the proper mix and depth of credentials for the purpose of the review. (14) It would be helpful to have a list of reviewers prior to the meeting. (20) Don't know who are the reviewers.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 0; 4 = 2; 5 = 0 *Don't know their credentials* = 4
D-8	There were no problems with the numerical rating schemes used. (3) What is "numerical rating scheme?" We were not informed of this "scheme." (20) Don't know the schemes.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 1; 4 = 1; 5 = 1 *N/A* = 2
D-9	Altogether, the preparatory materials, presentations, and the Question & Answer period provided sufficient depth of review.	*disagree* *agree* 1 = 0; 2 = 0; 3 = 1; 4 = 4; 5 = 1

(11)Answers to D-5 through D-9 N/A as reviewer's responses had not been seen yet.

Appendix G – Input for PEEM Technology Needs for PHEV Application

[a]Which projects currently in the DOE portfolio would be applicable to PHEV needs?

[b]Would the technical targets for these projects change substantially for PHEV applications?

(1) All current electric machines and power electronics projects apply to PHEVs. Cost goals for PHEVs need to be more aggressive than charge sustaining hybrids, but in line with FreedomCAR targets.

(2) [a]Most.
[b]Not much (for many projects).

(3) Applicable projects: inverters, dc-dc converters, and high temperature converters. High speed motors.

Target changes: continuous power and power density have to be greater than the current targets. Add "round trip" (from charge to battery then battery back to wheel) efficiency target needs to be added.

(4) Systems with Prius-sized electric drives (~50 kW/55kW peak and 30 kW continuous) and larger should directly apply to PHEV systems, though they may not be optimal. Systems work that combines motors, inverters/converters together with thermal controls will be key.

(5) All projects are on track based on the "tech team" road map. Should the road map be reviewed against the PHEV needs first?

(6) [a]16K rpm IPM, J. Hsu; CPSR enhancement, J. McKeever; Integrated dc-dc, Gui-Jia Su; high-temperature inverter, Semikron; and polymer film and nano-dielectrics, Tuttle; thermal control of motors, J. Hsu; and air cooled power electronics, D.B.
[b]Yes, the PHEV demands will tilt the balance into higher capability electric propulsion and storage systems. Project time lines right now don't appear to mesh with PHEV schedule (I'm assuming a 2009 time frame).

(7) Nearly all current projects seem as applicable to PHEVs as HEVs or FC vehicles.

(8)

- IPM reluctance machines
- SiC switches
- Isolated dc-dc converters = triple voltage, dual voltage
- Capacitor development
- Thermal control

Power ratings will be much higher for PHEVs. Given the available space in a vehicle, power densities of inverters and motors may need to be increased substantially.

(9) PHEV is a difficult equation. Must be done at lowest cost from electrical side as real value is in added batteries. Would look at options for technologies to be on board or off-board vehicle. Cost may be very different in these two cases.

DOE projects on air-cooling likely are the better aligned projects.

(10) PHEV will place increased demands for power generation, thermal management, and temperature stability on the power electronics and motors. All projects are relevant. Projects focused on high temperature devices (SiC, wideband gap, caps, magnetics, and packaging) along with advanced cooling are especially important given the higher demands. Also important are projects that promise improved power density and specific power.

(11) Don't get caught up in the hype over PHEVs. Near term PHEVs, assuming battery is available, will launch off parallel hybrid offerings (Prius and Escape) which we are working hard today. 35–50 kW drives will necessitate ICE assist throughout drive (no extended EV mode). At some time when a larger battery is truly viable, series hybrids will become an option. There too we are covered by the work at putting a FCEV propulsion system on the book shelf.

- Keep us focused on what we are trying to accomplish in the road map.
- The only tech team that needs to work PHEV specific challenges is EES to drive Li Ion to viability.
- USATT can support policy and definition needs of DOE.

(12) Assuming that by definition a PHEV would have to be able to operate in "all electric" mode, then the two biggest changes would be the need to scale up the rating of all parts of the electric power train (storage, inverters, motors) plus the need to use a propulsion scheme more like that in a "series hybrid" than a "parallel" system like the Prius.

Are there technical challenges unique to PHEVs that are not being addressed in the current portfolio? If so, what are they?

(1) Some of these ideas are not unique to PHEVs, but are technical challenges that should receive some attention:

1. Low cost rotor position sensing for motors. Resolvers and encoders are expensive and/or fragile, and can probably be eliminated with research and demonstration.
2. Higher power motors and controllers, since many PHEVs will be larger vehicles with more power than is available from fuel cells.
3. More attention to how the power goes from the motor to the wheels; i.e., transmissions and gears and connection to the IC engine.
4. Evaluation of failure modes and affects (FMEA) and reduction of serious failure potential.

(2) Battery systems (at least high level interaction).
Recharge/generator (including regenerative braking) capabiity.

(3) Yes, e.g. deeper discharge and related problems for control and power electronics. Deeper discharge means wider battery voltage change which stresses further the power electronics and motors.

(4)

- Vehicle charging and power electronics (inverter) to connect to the utility grid.
- A modeling effort to examine the system issues (component sizes, duty cycles, thermal loads)
- Need a joint study with energy storage examining the life-verses control (SOC range) issues for batteries and control. How the power electronics control batteries has a huge impact on battery life.

(5)

- Battery system is in closer link to APPEM system for PHEV than for HEV. If charger, BMS, power/energy management to realize 40 miles ZE goals.
- Charger, BMS, power/energy management projects need to be added.

(6)

- Yes. For one having APEEM coordinated with USABC on energy storage technologies and second having systems level work on managing energy and power flows, i.e., energy management strategy.
- Plug-in issues/concerns with type plug (galvanic vs. paddle–the GM vs. Ford debate of Batt-EV days). On board vs. off board chargers.
- Scaleability concerns that will impact thermal controls more so than machines and power electronics.

(7) Could be more emphasis in:
- vehicle control algorithms and energy management
- study into overall vehicle efficiency of PHEVs vs. HEVs, ICEs
- motor control algorithms for increased efficiency over typical drive cycles.

(8) Power electronics for interfacing a larger battery pack.

(9) Focus on items that enable reduced cost in the areas of electronics power conversion; silicon, thermal interface, capacitors. More effort on enabling technologies for "classical" designs and less effort on "topology of the month." Let industry work up-integration within architecture for PHEV.

Also, help will be needed with power management and charger for charging interfaces.

(10)

- Battery charge and recharge cycles and load on batteries.
- Add in projects for power electronics for the batter charger systems.

(11) No, with exception of battery charger, which is well understood and a minimal cost.

(12) The need to have a propulsion system both configured and sized to satisfy all of the motor requirements without starting the engine would be the new direction.